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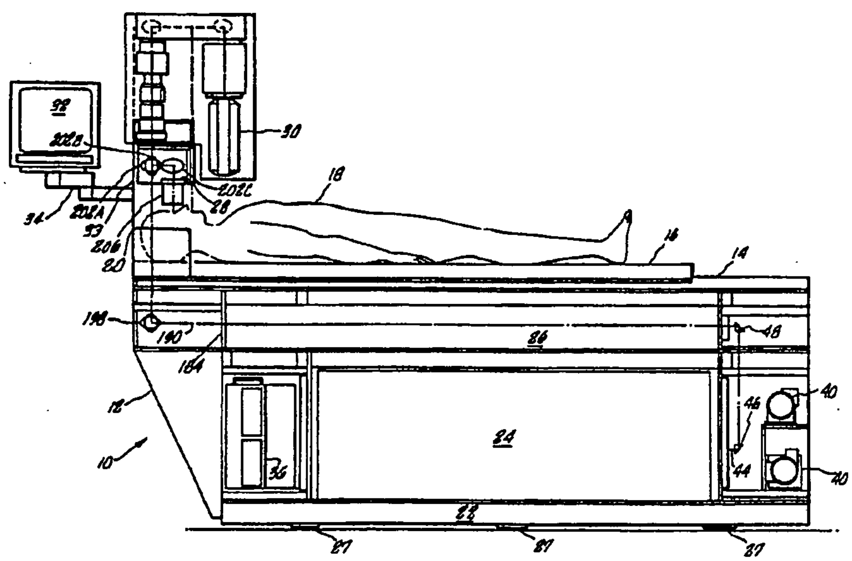

(57) Abstract

A laser system is capable of producing a plasma in a target irrespective of whether the target (18) is absorbing or non-absorbing for the laser pulses. This system is particularly useful for making precise cuts in animal tissue for laser surgery such as for opthamological procedures. The system including a generation zone (24) for generating a principal lasing radiation pulse (44), an shortening zone (56) for shortening the duration of the principal pulse, a pulse multiplier (102) that multiplies the shortened pulse to a plurality of temporally, and preferably spatially, spaced apart pulses, and a beam delivery system (28) that focuses the spaced apart pulses into a sufficiently small spot size to achieve an irradiance of at least about 10^{13} watts/cm^2 in the target. A pulse shortener achieves substantial pulse shortening using amplified spontaneous emission.

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WEST

PRECISION LASER SYSTEM USEFUL FOR OPHTHALMIC SURGERY

BACKGROUND

The present invention relates to laser systems, and more specifically to laser systems especially well-suited for medical and industrial applications.

Generally a laser operates on a target by destroying a portion of the target. The laser is chosen so that at the wavelength generated by the laser, the target absorbs energy in a sufficient amount to obtain the desired effect.

Exemplary of the uses of a laser are those in medicine. For example lasers can be used for cutting tissue such as removing foreign bodies and polyps on eyelids. A commonly used laser for this purpose is the carbon dioxide laser operating at a wavelength of 10.6 microns; at this wavelength water molecules absorb strongly. Since water is a basic constituent of animal tissue, the laser light is absorbed by the tissue.

Other applications include ophthalmic surgery where, for example, cuts can be made in the iris. For many ophthalmic applications it is necessary to select a wavelength that passes through the cornea with substantially no absorption by the cornea, with preferential absorption by the iris.

Although many existing laser systems are suitable for applications such as medical applications, they are not without disadvantages. For example, a different laser system is required for each particular application depending upon the absorption characteristics of the target. Thus a hospital operating room can require more than one laser, a different laser for each surgical procedure.

Another problem with many existing laser systems is that there is a risk of damage to surrounding tissue. This can occur because biological tissues are broad band absorbers. Tissues surrounding the target region, for example the cornea in front of the iris, can absorb some of the incident lasing radiation, with undesired damage to the cornea. In addition the spot size of the focused laser pulse can be so large that it is difficult to make precise treatments without undesired damage, and particularly without thermal damage to tissue surrounding the target region.

Another disadvantage of many existing laser systems is that the width of the cut made is fixed, and cannot be adjusted, and the depth of the cut is greater than desired. For example, the present state of corneal

refractive surgery entails making surgical wounds from the exterior to a predetermined level of the stroma. It has been discovered that the ability to control the depth of such wounding, which is often full thickness, is difficult, and furthermore that the healing of such wounds can vitiate the intended effects of altering the curvature of the cornea, either for high refractive errors or astigmatism. Inability to accurately control the size and location of incisions made with a laser can have adverse consequences. For example, in corneal surgery each incision has an optical as well as an anatomical effect. Attempts to accurately modify corneal curvatures by relaxing incisions and thickness volume modification have met with some clinical success but the accuracy of correction obtained remains too erratic to justify their routine clinical use, especially in otherwise normal eyes.

Similarly, corneal incisions for cataract and keratoplasty often induce excessive astigmatism necessitating secondary surgical correction.

Further, conventional corneal surgical incision or refractive modification requires that Bowman's membrane be compromised with the result that continuous and variable refractive changes are induced. Corneal curvatures could be more readily quantifiable and better maintained or modified by surgical intervention if Bowman's membrane could be preserved intact during corneal incision or ablation of deeper stromal structures.

Attempts have been made to develop laser systems to make precise cuts using ultrashort pulses to minimize both thermal and non-thermal damage. With an ultrashort narrowly focused pulse, damage can be limited to a very small region in the target. However, with narrowly focused ultrashort pulses, it is extremely difficult to make incisions and other cuts at a sufficiently fast rate to be feasible for most medical and industrial applications. For example, for a pulse duration in the order of 10 picoseconds, with an elapsed time between pulses of 50 picoseconds, the targeting system used must be capable of moving the targeted focal point of the laser within 50 picoseconds. If the damage zone is 10 micrometers, it is necessary to reposition the target zone at a speed of 20,000 meters per second (10 micrometers/50 picoseconds), which is infeasible to achieve. Thus it is extremely difficult to have a combination of very small damage zones with ultrashort pulses using conventional laser systems.

Another problem with ultrashort pulse systems is that it can be difficult to achieve consistent energy levels from pulse-to-pulse, i.e. output jitter occurs. This can result from inadequate synchronization between a laser used for generating the ultrashort pulse and the laser used for amplifying the ultrashort pulses to an energy level sufficiently high to treat a target. Jitter

can result in inconsistent treatment of a target with some target regions being under treated and other regions of the target being excessively damaged.

A further problem with many existing laser systems is that they are difficult to align and are mechanically complex, leading to frequent breakdowns.

In view of these problems with existing systems, there is a need for a laser system that provides ultrashort pulses and small target zones where the size of the target zone can be controlled to make precise cuts at useful rates. Further there is a need for a system that is mechanically simple, easy to align, and can be used effectively for biological tissues without damaging surrounding tissue such as tissue between the laser and the target zone.

SUMMARY

The present invention provides a laser system that satisfies these needs. The system comprises means for generating principal lasing radiation pulses, a pulse shortening system or zone for shortening the duration of the principal pulses, preferably a pulse multiplier system or zone for increasing the number of pulses, and a beam delivery system including focusing means for focusing the output pulse into a sufficiently small spot size in the target to achieve irradiance in the target sufficient for forming a plasma irrespective of whether the target is absorbing or non-absorbing for the output beam wavelength. The irradiance achieved in the target is at least 10^{13} watts/cm^2, as much as 10^{15} watts/cm^2, and can be greater.

The principal lasing radiation pulses can be generated with an excimer laser generating input pulses and a beam splitter splitting each input pulse into a pumping pulse and the principal pulse. The pumping pulse is used for pumping amplifier lasers in the shortening system and the pulse multiplier system.

In the shortening system, the duration of each principal pulse is shortened with a cascading series of shortener/amplifier stages. Each stage comprises at least one pulse shortener that shortens the duration of each principal pulse and at least one pulse amplifier that amplifies each principal pulse. The first pulse shortener is activated by each principal pulse. Each shortened pulse emerging from the first pulse shortener is amplified in the pulse amplifier of the first stage. The radiation emerging from each stage is directed into a pulse shortener of the next successive stage, and the pulse emerging from the pulse shortener of each stage is amplified by the pulse amplifier of that stage before being directed to the next stage. This system is effective for shortening the duration of a pulse so that the emerging pulse has a duration of less than about 1/100 of the input pulse. For example, where the duration of the principal pulse is 1 nanosecond or greater, the duration of the pulse emerging from the shortening system can be less than 100 picoseconds, preferably less than 10 picoseconds, and can be as small as about 1 picosecond.

A preferred pulse shortener according to the present invention comprises a dye solution capable of absorbing energy from incoming radiation pulses and

means for containing the dye solution comprising a front or entrance window and a rear or exit window. Both windows have an interior surface. The front window is capable of transmitting at least a portion of the incoming pulses into the dye solution. Optical means are positioned in front of the front window for optically focusing the incoming radiation pulses through the front window into the dye solution at a focus between the windows for generating radiation in the dye solution by amplified spontaneous emission. Both windows are substantially transparent to the generated radiation with the front window reflecting a portion of the incident generated radiation to the focus. The focus is sufficiently close to the front window so that reflected generated radiating reenters the active focal region prior to the initiation of lasing. This quenches any stimulated emissions occurring in the region of the focus to avoid lasing, thereby both amplifying and shortening the outgoing pulse. Generated radiation passes through the rear window as an output pulse with substantially no reflection of the generated radiation from the rear window to the focus. The focus is at a location between the front and rear windows such that each incoming lasing radiation pulse has a single respective outgoing pulse of shorter duration.

An advantage of this system is that it is easy to use. The duration of the outgoing pulse can be controlled by adjusting the optical means for changing the location of the focus in the dye solution with reference to the first window. The duration of each outgoing pulse can be less than about one half of the

duration of its respective incoming pulse, and preferably is less than about 1/10 of the duration of its respective incoming pulse.

Typically the front and rear windows are spaced apart by at least 1 mm, and the focus is closer to the interior surface of the front window than it is to the interior surface of the rear window. The distance between the focus and the interior surface of the front window preferably is at least 30% of the distance between the two interior surfaces. To prevent any generated radiation reflected by the rear window from reaching the focus, the rear window can be slanted at an angle relative to the outgoing pulses, such as by being placed at the Brewster angle.

An important advantage of pulse shorteners according to the present invention is that they can be operated with substantially no pulse-to-pulse variation in the amount of amplification achieved in the amplification stage, i.e. substantially no jitter. Because the shorteners operate on the principal of amplified spontaneous emission rather than stimulated emission, it is possible to operate a shortener/amplifier stage with a single excimer laser using a beam splitter to provide the pumping pulse for the amplifier. Because the same laser provides the pumping pulse and the input pulse to the shortener/amplifier stages, there is no problem synchronizing the pumping pulse and the input pulse to achieve consistent amplification in each amplification stage. This ability to achieve consistent amplification from pulse-to-pulse results in consistent and reproducible treatment in the target.

As noted above, a practical difficulty with ultra- short pulses, particularly narrowly focused ultrashort pulses, is that it is difficult and time consuming to make large cuts. To increase the number of pulses at the target without losing the advantages of having ultrashort pulses, a pulse multiplication zone or system is used for multiplying the number of pulses. In the pulse multiplication zone there is at least one pulse multiplier that produces a plurality of temporally spaced apart pulses for each pulse entering the pulse multiplier. Preferably the pulses generated in the pulse multiplier are also spatially spaced apart from each other. By "spatially spaced apart" there is meant that when the pulses are focused by a suitable lens, the focused pulses are spatially spaced apart.

A pulse multiplier according to the present invention comprises a closed cell comprising a front window and a rear window, both windows having an interior surface and substantially the same index of refraction. There is a medium in the cell having an index of refraction substantially equal to the index of refraction of the windows and substantially transparent to the incoming lasing radiation. The cell also contains front and rear opposed reflective means in contact with the medium, preferably with at least one of the reflective means being curved so that the outgoing pulses are spatially spaced apart. Preferably the front and rear reflective means comprise the interior surface of the front and rear windows, respectively. The reflective means have a reflectivity of at least about 80% for the incoming lasing radiation pulses.

By the term "substantially transparent" medium or window there is meant that the medium or window transmits at least 90% of the relevant radiation therethrough.

With this pulse multiplier, a portion of each incoming lasing radiation pulse is transmitted through the front window into the cell for reflection back and forth between the reflective means. A portion of each pulse impinging on the rear reflective means passes through the rear window as one of a series of temporally spaced apart outgoing lasing radiation pulses. Because at least one of the reflective means is curved, the outgoing pulses are spatially spaced apart from each other. The windows can be spaced apart from each other by a distance from about 1 to about 100 mm, and preferably from about 5 to about 20 mm, depending upon the time gap desired between sequential pulses.

In a preferred version of the invention, means are provided for changing the curvature of the reflective means for changing the amount the outgoing pulses are spatially spaced apart from each other. This can be effected with a fluid medium in the cell by varying the pressure of the fluid with control means. The curvature can be controlled so that the outgoing pulses when focused are spatially spaced apart from each other by as little as 1 micron, and by as much as 10 microns and more.

Successive pulses exiting from the pulse multiplier have a smaller peak power, depending upon how many times the lasing radiation was reflected back and

forth by the front and rear reflectors. For effectively working with a target, it is important that the pulses reaching the target all have about the same peak power. This is effected by amplifying the output pulses from the multiplier in at least one pulse amplifier for amplifying the spaced apart pulses to produce high power output pulses and low power output pulses. The low power output pulses have substantially less peak power than the high power output pulses, and generally a peak power less than about 1/10, and more preferably less than about 1/100 of the peak power of the high power output pulses. Thus the low power output pulses are insignificant. There are at least 2, and preferably at least 5 high power output pulses having about the same peak power for each pulse entering the pulse multiplier. A plurality of pulse multipliers can be used in series for further multiplying the pulses.

Preferably the pumping pulse developed in the generation zone is used for pumping all of the amplifiers of the present system. For the amplifiers after the pulse multiplier, it is possible to selectively amplify some of the spaced apart pulses more than others by delaying the arrival of the principal pulse at that amplifier. Thus, the number of high power output pulses produced for each imput pulse to the pulse multiplier can be controlled by controlling the timing of the arrival of the pumping pulse at the amplifier relative to the arrival of the spaced apart pulse from the multiplier.

This system provides output pulses that have a near Gaussian transverse spatial profile, which is important for achieving a small spot size in the target. A beam delivery system for achieving a small spot size includes focusing means for focusing the output pulses in the target with a pair of lenses that expands and collimates the output pulses. The expanded and collimated output pulses are passed through a focusing objective lens, and means are provided for controlling the focal plane of the focusing objective lens. The focusing system can focus the pulses to a spot size of less than 10 microns, such as 2 microns, with means of a wide cone angle of 30-40 degrees.

The laser system of the present invention can have an imaging system whereby imaging signals are focused on the target and signals emanating from the target as a result of the imaging signals pass along an imaging path and are collected by collecting means for display by display means such as a video screen. The focal plane of the focusing objective lens for the lasing radiation pulses is controlled so that the focal plane of the imaging system and the focal plane of the focusing objective lens are the same. Preferably the focused imaging signals and the focused lasing radiation pulses are colinear for ease in operation. Backscatter of laser pulses from the target to the imaging system can be avoided by polarizing the laser beam with a first polarizer and placing a second polarizer in the imaging path, the second polarizer being at a 90° rotation relative to the first polarizer.

This lasing system has many substantial advantages. For example, ultrashort pulses are formed, generally less than 100 picoseconds, and preferably less than 10 picoseconds. These short pulses minimize damage to tissue surrounding the target region.

Further, precise small cuts can be formed. Due to the near Gaussian distribution of the lasing radiation pulses and the wide cone angle of the focusing system, spot sizes of less than about 10 microns can be achieved. Wide cuts can be made by controlling the spacing between the pulses generated in the pulse multiplier. Controllable cuts having a width of from about 10 to 100 microns are possible. Because of the pulse multiplier, it is possible to achieve cuts that are the same width and length of prior art cuts where the cuts have a very shallow depth, smaller than obtainable with prior art systems.

Due to the combination of a very small spot size and ultrashort pulses, a plasma can reliably be formed in the target. The plasma is formed without requiring absorption by the target. Thus targets that are transparent to lasing radiation can be treated. The invention allows formation of a precise and localized damaged zone because the energy transferred does not depend on a selective absorption mechanism. Rather, the laser beam transfers substantially no energy except to the plasma in the sharply defined region of plasma formation. The operative wavelength can be chosen to maximize transmission to the target region since the energy transfer mechanism does not rely on absorption. This results in a high degree of safety for non-targeted regions.

Further a single laser system can be used for multiple procedures; there is no need to change the wave- length of the output radiation or to change laser systems to accommodate the absorption characteristics of a particular target. This can allow an operating room to be equipped with one laser system rather than a multitude of systems.

A further advantage of a system embodying features of this invention is that targets that are screened from the lasing radiation source, such as the iris which is screened by the cornea, can be operated on without adversely affecting the screening tissue, i.e. the cornea. Because of the wide cone angle, which allows a very small spot size focus, screening tissue in front of the target is not damaged.

Another advantage of a system according to the present invention is that due to the frequent pulses resulting from a single pulse multiplier, which can be in the order of 10 to 300 times per second, to as many as one billion pulses per second with more than one multiplier, operations can be effected efficiently and quickly.

A system according to the present invention is mechanically dependable and easy to align since the key components, namely the pulse shorteners and the pulse multipliers, are front in/back out devices, i.e. the pulse enters through a front window and exits through a back window.

In a preferred version, the pulse amplifiers used are dye lasers. This allows the system to be used with substantially any incoming wavelength merely by tuning or changing the dye used.

Further, the system can be used with varying incoming pulse durations merely by changing the position of the focusing means used with the pulse shorteners for controlling the amount the incoming pulse is shortened.

DRAWINGS

These and other features, aspects, and advantages of the present invention will become better understood with reference to the following description, appended claims, and accompanying drawings where:

Fig. 1 is a front elevation view of a laser surgery apparatus embodying features of the present invention;

Fig. 2 is a flow sheet showing portions of the laser system of the apparatus of Fig. 1;

Fig. 3 is a schematic view of a shortening apparatus for use in the laser system of Fig. 2;

Fig. 4 is a schematic view of another pulse shortening apparatus for use in the laser system of Fig. 2;

Fig. 5 is a side elevation view, partly in section, of a pulse multiplier apparatus that can be used in the system of Fig. 2; and

Fig. 6 is a schematic view of a beam delivery system and monitoring system for use with the apparatus of Fig. 1.

DESCRIPTION

1. Overall System

Fig. 1 shows an apparatus according to the present invention useful for surgical procedures on the eye. The apparatus is capable of treating a target with ultrashort, narrowly focused, high power lasing radiation pulses at a high firing rate for generating a plasma in the target irrespective of whether the target is absorbing or non- absorbing for the lasing radiation pulses. The system is capable of generating from 1 to 30 bursts per second, each burst having at least 10 pulses (from at least 10 to 300 pulses per second), each pulse creating a damage zone with a diameter of from 6 to 100 microns, the distance between focal points of the pulses within each burst being controllable from 0 to 100 microns. The pulses have sufficient power that the irradiance achieved in the damage zone is at least 10^{13} watts/cm^2 which is sufficient to form a plasma in most materials and in substantially all biological materials.

With reference to Fig. 1, an apparatus 10 suitable for laser opthalmic surgery comprises a frame structure 12 providing a top surface 14 for supporting a patient on a support pad 16. A patient 18 is on the support pad 16 in a prone position with the patient's head held firmly by a head restraint 20.

The frame assembly includes a base 22 on which is supported an input laser system 24. The input laser system 24 can be housed separately in a vented space outside the operating suite. Mounted above the input laser system 24 and below the patient is a laser pulse processing system 26. The frame structure 12 includes a plurality of leveling mounts 27 on its bottom for leveling the apparatus.

Above the head of the patient are a beam delivery system 28 and an imaging system 30 that includes a viewing monitor 32. The delivery system 28 and the imaging system 30 are supported by a rigid, damped main gantry frame 33 that is above the head of the patient 18 and that is attached to the main frame structure 12 at the head thereof. The viewing monitor 32 is supported by an arm 34 extending from the gantry frame 33. The beam delivery system 28 is controlled by a controller system 36. The controller system 36 is at the head portion of the frame 12 adjacent to the input laser generating system 24. At the foot of the frame structure 12 are provided the utilities for the processing system 26 such as vacuum pumps 40 that serve to circulate and purge the gas used with the input laser system 24.

A plurality of lasing radiation pulses 44 are generated by the input laser system 24. These pulses are split into pumping pulses and principal pulses. In the processing system 26 each principal pulse is shortened and then multiplied to produce a plurality of spatially and temporally spaced apart pulses. The spaced apart pulses are then amplified in the processing system 26 and directed to the beam delivery system 28

for focusing at a selected target in the eye of the patient 18. The imaging system 30 allows the operator to visualize where on the target the beam delivery system 28 is focusing the lasing radiation pulses. The control system 36 is used to control the location of the damage zone in the target.

2. Pulse Generating and Processing Systems

A. Generating System

excimer

With reference to Figs. 1 and 2, the generating system 24 comprises an input laser 42 that produces a plurality of input pulses 44. Preferably the generating laser 42 is an XeCl excimer laser for long life, reliability, and sufficient power to create a plasma in the target region. A suitable excimer laser provides pulses of from about 40 to 2000 mj, the pulses having a duration of about 5 to about 8 nanoseconds with a frequency of about 30 hertz.

Each input pulse 44, which is directed generally horizontally by the input laser 42, is redirected vertically by a first reflector 46 and then horizontally by a second reflector 48 for use in the processing system 26 in the upper portion of the frame structure 12. Thereafter the pulse is divided by a first beam splitter 50 so that about 90% of each pulse is available as a pumping pulse 52 for pumping dye laser amplifiers as described below, with the remaining 10% portion 53 of the pulse being reflected by a third reflector 54 as a principal pulse 56 for further processing. Each of the first 46, second 48 and third

54 reflectors can be an aluminum mirror or a right angle prism. The first 46 and second 48 reflectors serve to provide a compact shape for the apparatus 10.

An important advantage of a system according to the present invention is that a single excimer input laser 42 can be used to provide the pumping pulse 52 using for pumping dye cell amplifiers and the principal pulse which is processed to produce a plurality of ultrashort pulses. Use of a single input laser eliminates the need to synchronize two or more lasers, thereby reducing jitter in the output pulses used for treating the target.

In Fig. 2, the double headed arrows adjacent different components of the system indicate the degrees of freedom of movement available for each component for setting up the system and for controlling the parameters of the output pulses including their duration, frequency, and energy. The arrow symbols have the following meanings:

< >	One dimensional translation generally horizontal
<	>	Two dimensional translation generally horizontal and vertical
<	>	Three dimensional translation

The processing system modifies the principal pulses to achieve output pulses with the following properties:

(1) a near Gaussian transverse profile;

(2) a pulse duration sufficiently short to avoid damage to tissue surrounding the target region, generally less than about 100 picoseconds, preferably less than about 10 picoseconds, and most preferably about 1 picosecond;

(3) a sufficiently high frequency of pulses to create a dense plasma in the target region; and

(4) sufficient energy in the pulses to break the weakest chemical bond in the target region.

The pulse processing system includes a pulse shortening system, a pulse multiplying system, and a pulse amplifying system.

B. Pulse Shortening System

The pulse shortening system comprises a plurality of shortener/amplifier stages 56. In the version of the invention shown in Fig. 2, there are three stages 56A, 56B, and 56C in series. Each stage 56 comprises a shortener assembly 58 and an amplifier assembly 60. With regard to the shortener/amplifier stages, components of the different assemblies that are similar are given the same reference number, differing only in the suffix A, B and C for the first, second and third stages, respectively. Although each stage 56 is shown having a single shortener assembly 58 and a single amplifier assembly 60, in some instances one or more the stages can have more than one amplifier and/or more than one shortener. The amplifiers are required because the shorteners, in reducing pulse duration, also reduce the energy of a pulse. If an incoming pulse has sufficient energy and if the shortener assembly is sufficiently efficient, in some instances an amplifier immediately

after a shortener assembly is not required. The pulse shortening system generally includes at least one shortener and at least one amplifier.

Each shortener assembly 58 has a focusing lens 62 and a pulse shortener 64. Before the first focusing lens 62A there is a neutral density filter 66 that reduces the intensity of incoming pulses 56 to accommodate changes in the power of the input pulse 44. The first shortener assembly 58A also includes an iris diaphragm 68 after the pulse shortener 64A for spatial filtering by blocking diverging light such as that caused by fluorescence.

With reference to Fig. 3, each pulse shortener 64 comprises a dye cell 70 having a front window 72 and a rear window 74, where both windows can be made of quartz glass. Within this cell is a dye solution 76. Preferably the cell 70 is a continuous flow cell. The focusing lens 62 focuses an incoming pulse through the front window 72 of the cell into the dye solution for activating the dye solution at a focus 77 between the front 72 and rear 74 windows for generating radiation in the dye solution by amplified spontaneous emission. The front window transmits at least a portion of the incoming lasing radiation pulses into the dye solution. Both windows are substantially transparent to the generated radiation with the front window 72 reflecting at least a portion of the incident generated radiation to the focus 77. The front window 72, by reflecting generated spontaneous radiation to the focus 77, serves to quench any stimulated emissions so that no lasing occurs and only a single short pulse is emitted by the

shortener 64 for each incoming pulse. Preferably the front window transmits at least 90% of the incoming radiation pulses into the dye solution while the rear window reflects less than about 10% of the generated lasing radiation impinging upon it. The generated radiation is passed through the rear window 74 as an output pulse with substantially no reflection of the generated radiation from the rear window to the focus.

Sufficient quenching is achieved by the reflection from the inner surface 78 of the front window 72 by providing the front window with a reflectivity of about 4%, which occurs naturally with most quartz glasses. The reflection from the inner surface of the front window back into the active region of the dye at the focus reduces the excited population that remains in the active region for shortening and amplifying the output pulse.

The location of the focus 77 relative to the front window 72 and the rear window 74 is important to the operation of the shortener 64. If the focus 77 is too close to the front window 72, then there is more than one output pulse for each input pulse. Moreover as the focus 77 is moved closer to either the front or rear window, the duration of the output pulse increases. Generally the distance "d" between the focus 77 and the interior surface 78 of the entrance or front window 72 is less than about one half the distance "L" between the inner surface 78 of the front window 72 and the inner surface 80 of the exit window 74. In other words, generally the lens 62 is configured and adjustably positioned so that the focus 77 is closer to the front window 72 than it is to the rear window 74. To achieve

a single outgoing pulse of short duration, preferably the distance d is at least about 30% of L. The front and rear windows are generally spaced apart by at least about 1 mm and can be spaced apart by as much as 20 mm or more.

The front and rear windows can be planar as shown in Fig. 3. However, with reference to the version of the invention shown in Fig. 4, a front window 81 can have other shapes, including plano-convex, and as shown in Fig. 4, concave-convex where the convex surface is the inner surface 82. In the version of the invention shown in Fig. 4, the front window serves to focus the incoming light and any reflected light to the focus 77. The curvature of the inner surface 82 of the front window 81 shown in Fig. 4 is such that substantially all generated radiation reflected by the front window is reflected to and focused at the focus 77 for quenching.

Also as shown in Fig. 4, a rear window 83 can be inclined with respect to the optical axis to avoid any internal reflection from the rear window back to the focus 77. Preferably the rear window is inclined at the Brewster angle to avoid reflective losses at the rear window.

The focusing lens 62 can be any lens that focuses incoming pulses into the dye solution. For example, with reference to the first and second shortener assemblies 58A and 58B, the focusing lens 62A and 62B can be plano-convex. However, as shown in Fig. 2, the focusing lens 62C of the third shortener assembly 58C can be biconvex.

The amount of shortening achieved with the pulse shortener 64 can be varied by laterally moving the focusing lens 62 for varying the position of the focus 77 relative to the front and rear windows. It is possible for the outgoing pulse to have a duration less than about 1/2 the duration of the incoming pulse, and typically the duration of the outgoing radiation pulse can be less than about 1/10 the duration of the incoming pulse.

The dye used for each pulse shortener 64 can be substantially any dye that in the region of the focus at the wavelength of the incoming pulse can be optically excited by absorbing energy, and that when the threshhold for amplified spontaneous emission is reached, produces a short pulse.

An advantage of pulse shorteners according to the present invention is that they are easy to align which renders them ideal for mass production. Further they are adaptable to any incoming wavelength and pulse width merely by changing the dye material used and thus can be used with substantially any type of laser.

The pulse shorteners 64 generally have an energy efficiency less than about 10%. The output pulse from each shortener 64 has a peak power of about 1% of the peak power of the input pulse. Thus preferably an amplifier assembly 60 is associated with each pulse shortener assembly 58.

Each amplifier assembly 60 includes a beam splitter 84 and reflecting means such as a mirror 86 for directing a portion of the pumping beam 52 into an amplifier dye cell 90. Each amplifier assembly 60 also includes a focusing lens 88 for focusing the pulse from the preceding shortener 64 into the amplifier dye cell 90. Preferably the amplifier dye cells 90 are inclined at an angle of about 10° to normal to avoid internal reflections. The dye cell amplifiers 90 can be about 10 mm in light path, and preferably are continuous flow cells that contain the same dye as used for the immediately preceding shortener.

The focusing lens 88 of each amplifier assembly 60 can be any lens suitable for focusing, and preferably is a plano-convex lens. Each focusing lens 88 is laterally movable in order to control the position at which the pulses are focused in the dye cell for controlling the amount of amplification achieved. Generally amplification by a factor of from about 10 to about 100 can be achieved, i.e. the peak power of the output pulse from each amplifier assembly 60 is about 10 to about 100 times the peak power of the corresponding input pulse.

Although the dye cells have been shown as being pumped longitudinally to the input wave train, it is possible to use transversely pumped dye cells.

The amplifier assembly 60 of each shortener assembly 58 includes an iris diaphragm 92 which provides spatial filtering by blocking diverging light. After the iris diaphragm 92C of the last amplifier assembly 60 there is a gland laser polarizer 93 for polarizing the

light introduced to the pulse multiplying system. As described below, this polarizer 93 in combination with a second polarizer 229 avoids back scattering of the laser beam from the target to the imaging system.

With the cascaded shortener/amplifier stages 60, it is possible to modify an incoming pulse having a duration of 1 nanosecond or greater to an output pulse having a duration of less than 1/100 of the duration of the incoming pulse, i.e. the outgoing pulse has a duration of less than 10 picoseconds. For example the incoming pulse can have a duration of 5 nanoseconds or greater, and the outgoing pulse from the last shortener/amplifier stage 64C can have a duration of less than about 50 picoseconds.

More than or less than 3 shortener/amplifier stages 64 can be used in series, depending on the duration of the incoming pulse 55 and the desired duration for the output pulse.

C. Pulse Multiplier System

The principal pulse emerging from the last pulse shortener/amplifier stage 56C is introduced to a pulse multiplier system 94 that is capable of producing a plurality of temporally and spatially spaced apart pulses for each pulse entering the pulse multiplier assembly 94. The pulse multiplier assembly 94 comprises a pulse multiplier 102. With reference to Fig. 5, the

pulse multiplier 102 comprises a cell 103 having a front or entrance window 104 and a rear or exit window 106. Both windows 104 and 106 are coated with an anti-reflective coating on their outward facing surface 107 and 108, respectively, and are coated with a highly reflective coating on their inside facing surfaces 109 and 110, respectively. Inside coatings providing from about 80 to about 95% reflection, and preferably at least about 85% reflection are used, depending on the number of pulses desired from the pulse multiplier. Located in the region 152 between the windows is a medium in that is substantially transparent to the incoming lasing radiation and that has an index of refraction substantially equal to the index of refraction of the windows 104 and 106. It is important that the medium used not adversely effect the other components of the pulse multiplier, that it not absorb the incoming beam, and that its index of refraction substantially matches the index of refraction of the windows. Both windows have substantially the same index of refraction.

Rather than relying upon the interior surfaces of the windows for reflecting light, it is possible to use separate reflective means. In other words, the windows used to form the outer walls of the cell need not be the same structures that serve to reflect light within the cell. When desired that the reflecting means be the inner surface of both the front and rear windows, these windows can be coated with either aluminum or silver to create a reflector, or preferably a dielectric coating is used.

A portion of each incoming lasing radiation pulse is transmitted through the front window into the cell for reflection back and forth between front and rear reflective means, and preferably between the inside surfaces of the windows. A portion of each pulse impinging on the rear reflective means passes through the rear window as one of a series of temporally spaced apart outgoing lasing radiation pulses. Each outgoing pulse has less energy than the preceding pulse.

For spatially spacing the outgoing pulses apart, at least one of the reflective means is curved. Only a small amount of curvature is required. For example, for a cell where the windows are about 7.5 mm apart, with a rear window and a front window both having a concave interior surface with a radius of a curvature of about 1 kilometer, sequential pulses are spaced apart when focused by a distance of about 10 microns. Thus the curvature causes the outgoing lasing radiation pulses to be spatially spaced apart from each other.

The interior surface of the windows are spaced apart a sufficient distance, preferably at least 2 times the pulse width FWHM (full width, half maximum) of the incoming beam, that the outgoing pulses are independent and do not interfere with each other. However if the windows are too far apart from each other, then the corresponding pumping pulse used for pumping the amplifiers in the amplifier system (described below) that follow the pulse multiplier system are not able to adequately pump a sufficient number of output pulses to warrant use of the multiplier. Preferably the total separation between the first pulse and the last pulse that is amplified to a high power level in the

amplification system is less than one half the pulse width (FWHM). To achieve at least two independent output pulses, the reflective means, are spaced apart from each other by a distance of from about 1 to about 100 mm, and preferably by from about 5 to about 20 mm.

Preferably the pulse multiplier 102 includes means for changing the curvature of at least one, and more preferably, both of the reflective surfaces. This can be effected by using a fluid medium in the region 152 and varying the pressure of the medium with a pressure controller 112, where increasing the pressure increases the curvature, and thus increases the distance the outgoing pulses are spatially spaced apart from each other. The medium can also be a solid such as a piezoelectric material, for example quartz, that upon application of an electrical current exerts pressure on the reflective surfaces, thereby changing their curvature. An advantage of a piezoelectric material is that it can be used to form a rugged multiplier without problems associated with leakage of a pressurized fluid.

A multiplier according to the present invention can be configured as shown in Fig. 5. Such a multiplier has a supporting frame 113. The frame 113 has an internally extending support flange 114 with an inwardly extending rib 115. The front window 104 is supported at its periphery by the flange 114 and along the edge of its inner surface by the rib 115. A rubber cushion 116 is placed between the front surface 107 of the front window 104 and the rib 115. An O-ring seal 118 is provided in a groove 120 in the frame 113 between the periphery of the front window 104 and the inward facing surface of the flange 114. The front window 104

is held in place by a front retaining ring 122 that is secured to the frame 113 by eight cap screws 124. The lateral position of the front window 104 can be adjusted with three front adjusting screws 126 equidistantly spaced apart around the periphery of the front retaining ring 122 and threaded thereinto. Each of the adjusting screws 126 presses against a protecting block 128 of polymeric material such as Delrin (trademark) acetal resin that sits against the front surface 107 of the entrance window 104.

The rear window 106 is mounted on a Delrin (trademark) acetal resin holder 130, there being provided a spacer 132 between the inner surface of the holder 130 and the inner surface 110 of the rear window 106 for setting the distance between the front and rear windows 104 and 106. The spacer 134 is held to the rear window holder 130 by a plurality of screws 136. An O-ring 138 is provided between the rear window holder 130 and the frame 113 as well as between the rear window holder 130 and the periphery of the rear window 106. The rear window 106 is retained in position in the frame by a retaining ring 140 that is threaded into the frame 113. Three equidistantly spaced apart rear adjusting screws 142 extend through the rear window retaining ring 140 into contact with the window holder 130. By means of the front adjusting screws 126 and the rear adjusting screws 142, the distance between the front and rear windows can be adjusted. Further, by adjusting the adjusting screws the windows can be maintained at a desired orientation relative to the incoming pulses.

The frame 113 includes an opening 150 into the space 152 between the front and rear windows, the opening 150 being provided with a threaded connection 153. A fluid source (not shown) is provided through the threaded connection 153 for providing the medium in the space. In the preferred version of the invention, the pressure of the medium is adjustably controlled by the pressure controller 112. For example, for a gas, a cartesian diver or a bellows type diaphragm pressure medium regulator can be used. Preferably a controller 112 that maintains constant pressure is used. The frame is provided with an outlet bleeder opening 160 for reducing the pressure of the medium in the space 152 when desired.

To maintain the window aligned biasing means such as springs (not shown), can be placed in the region 152 between the mirrors, each spring pressing outwardly against both windows.

This device 102 is able to alter the spacing between focal points and successive pulses, and has a spacing sensitivity of less than 1 micron, i.e. it is possible to have the focal points of successive pulses less than 1 micron apart. The distance between the spaces is controlled by controlling the curvature of the front and rear windows. The pulse multiplier 102 is able to adjust the elapsed time between successive pulses by varying the distance between the front and rear windows. This is effected by increasing or decreasing the size of the spacer 132.

D. Pulse Amplifier System

It is desirable that all of the pulses reaching the target have about the same peak power. Since the pulses produced by the pulse multiplier have different powers, it is necessary to process these pulses to equilibriate their power. This is accomplished by amplifying the spaced apart pulses in the pulse amplifier system with at least one amplifier for selectively amplifying the spaced apart pulses to produce high power output pulses and low power output pulses. The low power output pulses have substantially less power than the high power output pulses. There are at least two high power output pulses having about the same peak power. Preferably the ratio of the peak power of the high power output pulses to the peak power of the low power output pulses are at least 10:1, and preferably at least 100:1.

The pulse multiplier system includes at least one, and preferably a plurality of amplifiers. As shown in Fig. 2, three amplifier assemblies 60D, 60E and 60F are provided. These are substantially the same as the amplifier assemblies 60A, 60B and 60C used with the pulse shortening system, comprising a beam splitter 84, a mirror 86, a focusing lens 88, a dye cell amplifier 90, and an iris diaphragm 92. In addition the first amplifier assembly 60D of the amplifier system includes a front iris diaphragm 171. The last amplifier assembly 60F, rather than having a beam splitter, has a mirror 87 for reflecting at least 99% of the remaining portion of the pumping pulse to the last amplifier 90F.

The purposes of the iris diaphragms 92 are to reduce noise, cut down on beam divergence, and for achieving a near Gaussian distribution. It is important to have a near Gaussian distribution so that the outgoing beam can be expanded and collimated for eventual focusing into a small spot size for achieving high irradiance in the target region.

Selective amplification of the pulses produced by the pulse multiplier is achieved by controlling the time at which the pumping pulse arrives at each of the dye cell amplifiers 90 relative to the time at which the principal pulse arrives. The time delay is controlled with an adjustable optical delay assembly 180. This assembly can be placed anywhere in the path of the principal pulse before the principal pulse arrives at the amplifier assembly. In the version of the invention shown in Fig. 2, the delay assembly 180 is placed between the first pulse shortener assembly 58A and the first pulse amplifier assembly 60A. The optical delay assembly 180 comprises three totally reflecting prisms 182, 183, and 184 serially arranged so that the outgoing beam from the delay assembly 180 is colinear with the incoming beam. A delay of about 2 nanoseconds induced by the delay assembly 180 can result in selective amplification of the pulses from the pulse multiplier so that at least 2, and up to about 10 output pulses, all having about the same peak power, are produced for each input pulse to the pulse multiplier 102.

Thus, in the pulse processing system 26, a single pulse from an excimer laser has been shortened to form a plurality of ultrashort pulses. Each incoming pulse from the excimer laser yields a burst of pulses, each burst having about the same total duration as the duration of the incoming pulse. For example a single excimer pulse of a duration of about 5 to about 8 nanoseconds with an energy of from about 40 to about 50 millijoules can be used to produce about 10 output pulses, each pulse having a duration of about 10 to about 15 picoseconds, the pulses being spaced apart by about 130 picoseconds, and having an energy level of at least 300 microjoules per pulse. The output pulses have a near Gaussian transverse spatial distribution. The energy of the output pulses can be varied to provide sufficient energy for forming a plasma in the target by increasing or decreasing the number of amplifier assemblies used in the amplifier system.

The dye amplifier cells 90 and the shortener cells 64 shown in Fig. 2 are adapted to allow replenishing fill of dye solution to circulate transversely to the direction of the pumping beam and transversely to the direction of the input principal pulse. However, in some instances it can be possible to use dye cells sealed at both ends to have a stationary and non-replenished supply of dye solution. If a circulating flow is desired, the windows of each cell are joined together along their sides and the top and bottom of each cell are equipped with appropriate connections and plumbing to allow the dye solution to be replenished.

3. Beam Delivery and Imaging System

The purpose of the beam delivery system 28 is to direct and focus output pulses 180 from the processing system 26 onto a target with a sufficiently high irradiance to produce a plasma. This comprises the steps of expanding and collimating the output pulses and focusing the expanded and collimated output pulses through a focusing objective lens onto the target. In order for the operator to see what is occurring, imaging signals are focused on the target, and signals emanating from the target as a result of the imaging signals, typically reflected imaging signals, are collected. For accurate control, preferably the lasing radiation pulses and the imaging light are colinear, and the focal plane of the lasing pulses and the focal plane of the imaging signals are the same. Because the imaging signals and the lasing pulses are colinear and go through the same objective lens, there is no alignment problem with regard to the imaging system and the beam delivery system.

With reference to Figs. 1 and 6, output laser pulses 180 from the processing system 26 are expanded and collimated in a beam expander/collimator 184. The beam expander/collimator 184 includes a short focal length plano- concave entry lens 186 provided with an anti-reflective coating and a relatively longer focal length plano-convex exit lens 188. The concave surface of the entry lens 186 faces outwardly and the planar surface of the exit lens faces outwardly. The distance between the two lens is adjustable for controlling the size of the beam 190 discharged by the expander/-collimator 184. Also by adjusting the distance

between the two lenses, it is possible to adjust the focus of the pulses on the target so that the focal plane of the pulses is the same as the focal plane of the imaging system. The beam expander/collimator 184 increases the beam diameter to a size that substantially fills the final focusing lens, thereby maximizing the final focusing lens effective f number. This results in a high cone angle and a beam spot of minimum diameter. Preferably the focal lengths of the entry and exit lenses are in the ratio of about at least 1:10 to increase the beam diameter by a factor of 10, and more preferably in a ratio of about 1:20 in order to increase the beam diameter by a factor of 20 such as from a diameter of 1 to 2 mm to a diameter of 20 to 40 mm. The maintain the lens spacing relatively small, a compound lens system can be used, such as a commercial microscope objective lens.

In an exemplary version of the invention, the incoming pulse has a diameter of about 1 to 2 mm and the corresponding outgoing pulse 190 has a diameter of about 38 mm. To achieve this, the entry 186 lens can have a focal length of about -20 mm and diameter of 13 mm, while the exit lens 188 has a diameter of about 38 mm and a focal length of about 190 mm. Two two lenses can be spaced apart by about 170 mm.

The expanded and collimated light 190 is directed to the positioner or aiming system 28 by a mirror 198. The aimer 28 includes suitable deflecting elements interposed in the beam path to effect desired displacement of the focus. The aiming system 28 can comprise three mirrors 202A, 202B, and 202C for

controlling the position of the focus in the X, Y and Z axes. The laser beam is initially parallel to the Y-axis and undergoes three successive 90 degree deflections. First as shown in Fig. 1, the beam is deflected by mirror 202A parallel to the X-axis, then by mirror 202B in a direction parallel to the Z-axis, and then by mirror 202C downwardly to travel along an axis parallel to the Y-axis. The position of the mirrors and thus the position of the focus is controlled by the control system 36, which can be operated by hand or foot controls (not shown) as desired.

The properly targeted beam is then focused by a focusing objective lens 206. A suitable focusing lens 206 is a standard 110 mm camera lens. The spot size in the target is determined by the effective speed of the final focusing lens 206, or equivalently, by the cone angle at which the beam is focused. The location at which the beam is focused by the focusing lens 206 is referred to as the "focus" and as the "spot location". The spot size has a diameter proportional to the effective f-number of the focusing objective lens 206. In order to provide a sufficiently small spot size, the focusing lens 206 is sufficiently fast that the cone angle is greater than about 16 degrees, preferably greater than 20 degrees, and most preferably at least 30 degrees. Equivalently, the focusing lens 206 preferably has an f-number less than about 3.5, more preferably less than 2.8, and most preferably about 1.4, and the beam is expanded to substantially fill the lens. For an f/1.4 lens used in a preferred version of the invention, the nominal cone angle is 39.3 degrees. Due to the large cone angle through the focusing objective lens 206, it is possible to have a small transverse spot

size. This maximizes the irradiance at the spot location, allowing operation at relatively low total energy. Moreover, operation at low total energy and the high rate of fallout of irradiance with axial or transverse distance away from the focus also serves to minimize any damage away from the target site.

The optics or imaging system 30 serves to provide the viewing monitor 32 with a magnified image of the region surrounding the focus for viewing by the operator. The imaging system 30 includes a light source 220 and a beam splitter 222 for directing a portion of the light from the light source 220 along the path of the lasing radiation pulses. The portion 225 of the imaging light not split to be colinear with the incoming lasing radiation pulses is collected in a first light dump assembly 224. The imaging light is directed to the target by the positioner system 34 along with the lasing radiation pulses and is focused in the target region by the focusing objective lens 206. A portion of the imaging light is reflected from the target, and is reflected by a second beam splitter 225 into an imaging lens 230 and therethrough into an eye piece lens 232 for delivery into an image intensifier 234. Light not split to the imaging lens 230 by the second beam splitter 225 can be dumped into a second light dump assembly 227. The imaging lens 230 can be a 50 to 300 mm zoom lens while the eye piece lens 232 can be a 20 mm enlarging lens. The imaging lens 230 cooperates with the focusing objective lens 206 to provide a real image, which is further magnified by the eye piece lens 232 and projected onto the active region of the image intensifier 234, which can be a silicone intensified target tube. The image is communicated by the image

intensifier to a suitable image processing apparatus such as the viewing monitor 32.

A second polarizer 229 is positioned between the second beam splitter 225 and the imaging lens 230. The second polarizer is rotated 90° relative to the first polarizer 93.

The light source 220 preferably is a collimated white light source. Other light sources can be used, including slit lamps, front lighting, a fiber optic conduit, the axial illumination system described above, or on any combination of these.

The beam splitter 222 used for directing visible light from the light source 220 and the beam splitter 225 used for directing visible light to the lenses 230 and 232 preferably are both broad band dielectric beam splitter that allow about 85 to 80% of the laser beam to pass therethrough while reflecting about 96% of the visible light. Thus the beam splitters transmit the laser pulse travelling toward the target while reflecting most of the visible light incident thereon. A suitable beam splitter is available from Newport Corporation of Fountain Valley, California under Model No. 20Q40 NC1.

In operating the system, the operating wavelength is chosen based upon the absorptivity of the material along the path to the target rather than on the absorptivity of the target itself. The wavelength is chosen for maximum transmission to the target for

minimizing damage to non- targeted regions and to insure that the bulk of the beam energy reaches the target.

EXAMPLES

Example 1

This example shows how the location of the focus 77 for a pulse shortener 64 affects the duration of an output pulse.

A XeCl excimer laser was used to provide an input pulse having a wavelength of 308 nm, a duration of from about 5 to about 8 nanoseconds, and an energy of from about 3 to about 4 mj. A micrometer controlled plano-convex focusing lens was used to focus the pulses into the pulse shortener 64 which had front and rear windows with a thickness of 1.25 mm. The windows were made of quartz and were spaced apart by 10 mm (interior surface to interior surface). Both the front and rear windows were perpendicular to the axis of the input pulse. The cell used was obtained from Hellma Gmbh of West Germany and was a Hellma Supersil UV quartz cell. The dye used in the cell was BBQ (see Table 2). The distance between the focus and the interior surface of the front window, d, was varied and the number of pulses and the pulse duration of the output were detected. The results are presented in Table 1.

TABLE 1

Effect of Location of Pulse Focus on Duration of Output Pulse from Pulse Shortener

Distance From Front Window d (mm)	Output Pulse Duration (Picoseconds)	Comments
3.00	2000	Multiple pulses
3.35	1600	Strong secondary pulse
3.53	800	Small secondary pulse
3.85	600	Single Gaussian pulse

The results presented in Table 1 show that if the focus is too close to the front window, non-Gaussian multiple pulses are produced. By having the focus at 3.85 mm from the front window, the pulse duration was reduced by about 90%.

Example 2

A system as shown in Fig. 2 was tested. The input laser 42 was an XeCl excimer laser available from Questek of Billerica, Massachusetts, Model 2400. The gas composition for the laser 42 was 30 mbar of HCl (5%) in helium; 20 mbar of xenon; and 2000 mbar of helium. Each output pulse from the excimer laser had an energy of 40 to 60 milijoules with a duration of 5 to 8 nanoseconds (FWHM), and a wavelength of 308 nanometers.

TABLE 2

DYE CELL PARAMETERS

Cell	Reference Number	Optical Path Length (mm)	Dye	Solvent	Concentration (Molar x10^{-4})
First shortener	54A	10	BBQ[1]	Toluene/ethanol (50/50)	1.5
Second shortener	54B	1	R590[2]	Ethanol	50
Third shortener	54C	1	R610[3]	Ethanol	50
First amplifier	90A	10	BBQ	Toluene/ethanol (50/50)	1
Second amplifier	90B	10	R590	Ethanol	5
Third-Sixth amplifiers	90 C, D E, F	10	R610	Ethanol	2.5

(1) 4,4''' - Bis [(2-Butyloctyl)Oxy]-1,1':4', 1":4",1"'-Quaterphenyl

(2) Ethyl o-[6-(Ethylamino)-3-(ethylimino)-2,7-dimethyl 3H-xanthen-9-yl] benzoato chloride

(3) [9-(o-Carboxyphenyl)-6-(diethylamino)-3H-xanthen-3-ylidene]diethylammonium chloride

The size of the dye cells and the dyes used for the pulse shorteners and amplifiers are presented in Table 2. Quartz dye cells from Hellma were used. The

dyes used in the amplifiers 90 were chosen so that the optimal absorption wavelengths of the dye solution were matched with the wavelengths of the pumping beam. The dye solutions for the shorteners 54 were chosen so the optimal absorption wavelengths of the dye solution were matched with the wavelengths of the incoming principal pulses.

Table 3 presents the focal length and diameter of the focusing lenses used in the processing system. Rather than using a plano-convex lens for focusing, a biconvex lens or a meniscus lens could have been used. All the lenses were constructed of quartz since ordinary

TABLE 3

FOCUSING LENS PARAMETERS

Lens	Reference Number	Focal Length (Inches)	Diameter (Inches)
First shortener assembly	62A	2	1
Second shortener assembly	62B	2	1
Third shortener assembly	62C	1	1
First amplifier assembly	88A	3	2
Second amplifier assembly	88B	3	2
Third amplifier assembly	88C	3	2
Fourth amplifier assembly	88D	3	2
Fifth amplifier assembly	88E	3	2
Sixth amplifier assembly	88F	3	2

The neutral density filter 66 reduced the energy of the incoming pulse by about 50% and had an outer diameter of 2 inches.

The adjustable optical delay line assembly 180 provided a path length of about 2 feet and delayed the principal pulse by about 2 nanoseconds.

The percentage of the light that each beam splitter splits out or diverts, based upon the energy of the incoming beam that is incident on the beam splitter, is presented in Table 4. The beam splitters were dichronic having a transmitivity on visible light of at least about 90% and a reflectivity at the wavelength of the pumping beam of 100%. All of the mirrors were dielectric mirrors having a reflectivity of greater than 95%.

The pulse multiplier 102 had the configuration shown in Fig. 5. The front and rear windows were each 1/2 inch thick and were made of glass with an anti-reflective coating on their outer surfaces. The glass is available from CVI, Inc. of Albuquerque, New Mexico under Catalog No. BW4-4050C (AR/85%). The interior surface of the glass had a reflective coating that reflected 85% of the incoming light. The front and rear windows were spaced apart by 11.4 mm. The space was filled with a perfluorochemical inert liquid available from 3M Co. of St. Paul, Minnesota under the trademark Fluorinert at a pressure of 2.5 psig. Both windows had an inside curvature with a radius of curvature of about 1 km.

TABLE 4

AMOUNT BEAM SPLITTERS SPLIT OUT*

Beam Splitter	Reference Number	Light Split Out* (%)
First	50	10
First Stage Amplifier	84A	4
Second Stage Amplifier	84B	10
Third Stage Amplifier	84C	20
Fourth Stage Amplifier	84D	20
Fifth Stage Amplifier	84E	30

*Amount splitter 50 diverts to third reflector 54

Table 5 presents the beam parameters for different positions along the beam path. For each position the number of pulses, the pulse duration, and the pulse energy are presented in Table 5. From Table 5 it can be seen that an input pulse having a duration of about 6,000 picoseconds and an energy of about 4,000 microjoules was converted to about 10 pulses, each having a duration of only about 10 picoseconds with a pulse energy of about 350 microjoules.

WEST

TABLE 5
BEAM PARAMETERS

Location	Number of Pulses	Pulse Duration (Picoseconds)	Pulse Energy (Microjoules
Input (44)	1	5000	4000
After first shortener	1	600	4
After first amplifier	1	600	90
After second shortener	1	100	1.5
After second amplifier	1	100	25
After third shortener	1	10	1.5
After third amplifier	1	10	30
After third multiplier	10	10	0.01
After fourth amplifier	10	10	2.5
After fifth amplifier	10	10	35
After sixth amplifier	10	10	350

The expander/collimator 184 had as an entry lens 186 a plano-concave lens 186 with the concave surface facing the incoming beam and having a focal length of -20 mm and a diameter of 13 mm, and as an output lens 188 a plano-convex lens with the planar surface facing outwardly, the convex surface having a 190 mm focal length and a diameter of about 50 mm. The distance between the two lenses was adjustable and was set at 170 mm. The incoming beam had a wavelength of 595 nanometers and a diameter of 2 mm, and was expanded to provide a collimated near Gaussian beam having a diameter of 38 mm.

The focusing lens 206 was a camera lens from Carl Zeiss of West Germany sold under the tradename Hasselblad Catalog No. 102150, the speed of the lens being f/1.4 and having a back focal length of 70 mm.

The imaging lens 230 was a Nikon zoom lens with a speed of f/4.5 and a focal length of from 50 to 300 mm. The eye piece lens 232 was a Nikon 20 mm f/2.8 lens. A Nikon F-C mount adaptor was used to connect the eye piece lens 232 to a Cohu (trademark) silicon intensified vidacom camera type image intensifier 234.

The system was tested on sutures having a 22 micron diameter in various tissues. The system provided about 15 bursts per second with 10 pulses per burst.

The pulses as originally tested were about 200 microns apart. The cone angle was wide, being about 35 degrees. Although the energy of each pulse was less than about 1 millijoule, because the pulses were focused in a spot size of about 2 microns, an irradiance exceeding 10^{15} watts/cm^2 was produced, resulting in plasma formation.

The tissues used were post-mortem Eye Bank eyes in which cornea and extraocular muscle tendon sheath were treated. The area to be targeted was identified with a 10-0 monofilament nylon suture passed through midstroma of the cornea and with a 6-0 black silk passed through the superficial layers of muscle tendon sheath. In the cornea the suture was placed in a four part mattress fashion so that when tied some tension was exerted on the suture loops. The laser beam

focused at the suture level and fired to make the suture to establish accuracy of alignment and focus. Subsequent laser bursts were directed at 90 degrees to the etched area in a linear fashion. Finally the suture was cut with the laser beam. All laser bursts were kept within the stroma of the cornea or superficial to the suture in the case of muscle tendon sheath. Overlying conjunctiva had to be removed in order to target muscle tendon sheath because of loss of normal transparency post mortem. Treated tissues were removed in block, fixated in gluteraldehyde 2% and formaldehyde 2% and embedded for electrom mocroscopy or for light microscopy. Postfixation tissue processing for electron microscopy utilized osmium in 0.15 M. sod. cacodylate buffer. Electron microscopy staining of ultrathin corneal specimens was done with lead citrate and uranyl acetate. For light microscopy hematoxylin and eosin stains were employed. The marking sutures enabled the pathologist accurately to identify the treated areas and to "back into" the treated area with serial sections. Suture tracts also provided control lesions adjacent to laser generated dehiscences.

Maximum calculated laser power densities were detected at targeted tissues. Tests were performed at 20 Hertz and the velocities were kept constant in order to create a linear lesion at the selected depth. At intervals the depth of the bursts was varied in cutting the suture of 22 microns using bursts of 2 microns. In all specimens a wave length of 595 nanometers with a pulse duration of 10 picoseconds was delivered at a cone angle of 30 to 40 degrees. This was focused into a spot size of 2 microns creating an irradiance density of about 10^{15} watts/cm^2.

Two Eye Bank corneal specimens, in each of which a 10-0 monofilament nylon suture had been placed in the mid- stroma and had received laser treatment causing interruption of the suture, were studied by light and electron microscopy. The light microscopic findings disclosed the suture track, and finally, in serial sections, the suture disappeared from the area of laser interruption creating a suture-free cavity in the mid-stroma. The anterior edge of this treated zone appeared roughened and irregular, while the posterior margin bordering the deep stroma had a compacted and slightly posteriorly bowed character. The epithelium throughout the entire specimen was completely denuded, probably an artifact from the late post-mortem acquisition of the tissue. Nonetheless, Bowman's membrane immediately in front of the treated area, Descemet's membrane, and the corneal endothelium all appeared to be unaffected at the light microscopic level by the laser therapy. One micron sections of the plastic embedded material showed a regular lamellar architecture on either side of the intrastromal suture away from the area of laser treatment. In the region of the laser treatment, however, irregular densities of the stroma were observed. Electron microscopic studies performed on suture material in the mid- stroma away from the laser treated area revealed the tract of the suture between lamellae. In the region of the laser treatment the normal collagenous architecture of the lamellae was disrupted. The collagen strands appeared to be broken, and moderate amounts of electron-dense debris were present in the field of the laser treatment. Larger electron-dense fragments appeared to be remnants of the suture material. The damage to the collagen

appeared to extend no more than three lamellae away from the tract of the suture (namely 20 x 40 microns).

The extraocular muscle tendon studied by light microscopy disclosed the absence of the conjunctiva, which had been peeled away due to its post-mortem opalescence to allow direct treatment of the tendon surface. In areas of the tendon at some distance from that of laser treatment, a clear-cut epitendinous connective tissue sheath, probably corresponding to Tenon's capsule, was applied intimately to the regular tendinous collagen. In the area that had been treated with the laser, as revealed by the presence of an introtendinous cavity where a 6-0 silk suture had been present for marking purposes, but removed for histopathologic sectioning, considerable thinning of the epitendinous connective tissue sheath was in evidence.

The light and electron microscopy studies of treated cornea and muscle tendon sheath demonstrated that a system according to the present invention operating at 595 mm ablated corneal stroma and superficial extraocular muscle tendon sheath. The small spot size and high power density created a minimal blast effect (damage zone) while creating well defined lesion. In corneal sections there was no evidence of laser damage to Bowman's or Descemet's membranes or their respective epithelial and endothelial layers. In muscle tendon sheath only the most superficial layers were disrupted, deeper layers being protected by energy absorption by the opaque tissue. Since power densities and spot sizes can be increased exponentially is anticipated that selectively deeper lesions can be achieved proportional to increased power densities and

spot sizes selected. In refractive surgery it should be possible, using intrastromal ablation, to create new corneal curvatures while preserving the anterior optical surface intact, significantly improving results. For example, graded removal of corneal tissue in plane from the corneal periphery would increase central corneal curvature to correct hyperopia. Conversely, removing graded layers centrally would correct myopia, as removal in sector would correct astigmatism.

Current muscle tendon surgery, even less accurate in its performance than corneal surgery, lends itself with considerable promise to intervention with a system according to the present invention. Trans conjunctival, essentially noninvasive, titratable, easily repeatable muscle weakening or strengthening procedures are feasible. By varying wavelengths, spot size and power density more or less tissue can be ablated either to allow lengthening (by nonthermal ablation) or strengthening (by graded thermal ablation) at a depth determined by the power employed.

4. Applications

A laser system according to the present invention has many applications. It can be used in physics and chemistry for such purposes as time measurement, and diagnostic purposes such as obtaining information on the structure and properties of molecules, as well as providing an instrument suitable for investigating plasma-plasma interactions.

There are many applications in biology and medicine for the system, including for diagnostics and

laser surgery. The system can serve as a scalpel and for treatment of a detached retina, vitrectomies, retinotomies, and to cure diabetic retinopathies as well as to remove foreign bodies and polyps on the eyelid, and for photocoagulation.

The system allows for focused intrastromal corneal wounds, without manifest damage to the anterior layers (epithelium, Bowman's membrane and superficial stroma), as well as sparing deeper stroma, Descemet's membrane, and the corneal endothelium. The ability to create controlled mid- stromal wounds is a significant improvement for corneal and refractive surgery and cataract surgery.

A laser system according to the present invention can be used for surgery within the mouth, such as for the removal of papillomas or tumors. It can also be used for treating bleeding lesions in the gastrointestinal tract. In dermatology this laser system can be used for removing tattoos and for treating some vascular diseases such as port wine stains.

A laser system according to the present invention can also be used for material working such as welding, cutting, drilling, surface treatment, and alloying. It is particularly useful for applications requiring high precision and minimum thermal damage such as the welding of microelectronic components and the drilling of hard materials. It is also useful for cutting and drilling ceramic materials for microelectronics and for resistor trimming. It can also be useful in telecommunications.

The laser system is also useful in applications where a substantially continuous high energy output pulse is required. By use of a plurality of pulse multipliers in series and parallel, and subsequent amplifiers, it can be possible to achieve a plurality of high power pulses.

Among the advantages of systems according to the present invention is that the system is mechanically simple and easy to align with respect to a patient. All of the components of the processing system are designed to be front in/back out system so that the principal pulse can travel in one continuous forward path. This allows for a compact laser system where the processing system can be placed in a relatively small area below a prone patient.

A significant advantage of a system according to the present invention is that it is possible to make precision cuts in regions as small as one micron without damage to surrounding tissue, including tissue between the laser light source and the target. The ultrashort pulses minimize damage to surrounding tissues.

Further, due to the pulse multiplier, it is possible to achieve large enough damage zones in a short time for such a precise laser system to be effective in such applications as a laser scalpel. Further there is substantially no variation in amplitude from pulse-to-pulse and burst-to-burst.

Moreover, due to the system's ability to create cuts regardless of the absorptivity of the target zone, it is possible to cut substances that heretofore

could not be efficiently cut. Moreover, a single laser system can be used for a wide variety of materials merely by changing the output wavelength such as by changing or trimming the dye used in the dye cells.

The system is easy to use because the imaging light and the laser beam are colinear and there is substantially no back scatter from the target to the imaging system; it is easy to target the beam at the desired target zone.

Because of the pulse multiplier, it is possible to achieve cuts with the beam that are the same or smaller width and length of prior art cuts in the same time but where the cuts have a very shallow depth, shallower than achieved with prior art systems. It is also possible to achieve precise tunneling. Although the present invention has been described in considerable detail with reference to certain preferred versions thereof, other versions are possible. For example, rather than using an excimer laser as the input laser, a Nd:YAG laser doubled or tripled in frequency can be preferable in some applications. Also rather than relying on longitudinally pumped dye amplifier cells, it is possible to use transversely pumped dye cell amplifiers. Therefore the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.

What is claimed is:

1. A method for forming a plasma in a target comprising the steps of:

(a) generating principal lasing radiation pulses;

(b) shortening the duration of the principal pulses in a pulse processing zone by the steps of:

(i) activating a first pulse shortener of a first stage of a series of shorteners/amplifiers, each stage comprising at least one pulse shortener that shortens the duration of the principal pulse by amplified spontaneous emission and at least one pulse amplifier that amplifies the principal pulse;

(ii) amplifying the shortened pulses emerging from the first pulse shortener in the pulse amplifier of the first stage with substantially no variation in the amplification from pulse-to-pulse; and

(iii) directing lasing radiation pulses emerging from each stage into a pulse shortener of the next successive stage, wherein the shortened pulses emerging from the pulse shortener of each stage are amplified with substantially no variation in the amplification from pulse- to-pulse by the pulse amplifier of that stage before being directed to the next stage,

the output pulses from the pulse processing zone having a duration of less than 100 picoseconds and having a near Gaussian distribution; and

(c) focusing the output pulses with focusing means into a sufficiently small spot size in the target to achieve an irradiance of at least 10^{13} watts/cm^2 in the target for forming a plasma in the target

irrespective of whether the target is absorbing or non-absorbing for the output pulse.

2. A method for forming a plasma in a target comprising the steps of:

(a) generating at least one principal lasing radiation pulse;

(b) processing each principal pulse in a pulse processing zone for producing output pulses suitable for focusing in the target, the step of processing comprising:

(1) shortening the duration of the principal pulse in a shortening zone by the steps of:

(i) activating a first pulse shortener of a first stage of a series of shorteners/amplifiers, each stage comprising at least one pulse shortener that shortens the duration of the principal pulse and at least one pulse amplifier that amplifies the principal pulse;

(ii) amplifying the shortened pulse emerging from the first pulse shortener in the pulse amplifier of the first stage; and

(iii) directing lasing radiation pulses emerging from each stage into a pulse shortener of the next successive stage, wherein the shortened pulse emerging from the pulse shortener of each stage is amplified by the pulse amplifier of that stage before being directed to the next stage;

(2) multiplying each shortened pulse emerging from the last pulse shortener/amplifier stage in a pulse multiplier that produces a plurality of temporally spaced apart pulses for each pulse entering the pulse multiplier; and

(3) amplifying at least a portion of the spaced apart pulses in an amplifier zone comprising at least one short pulse amplifier to produce high power output pulses,

the output pulses having a duration of less than 100 picoseconds and having a near Gaussian distribution; and

(c) focusing the output pulses with focusing means into a sufficiently small spot size in a target to achieve an irradiance of at least 10^{13} watts/cm^2 in the target for forming a plasma in the target irrespective of whether the target is absorbing or non-absorbing for the output pulses.

3. The method of claim 1 or 2 in which the target is non-absorbing for the output pulses, and wherein, preferably, the target is animal tissue and the output pulses pass through other animal tissue before reaching the target tissue.

4. The method of any one of claims 1 to 3 in which the target tissue is substantially transparent to the focused pulse.

5. The method of any one of claims 1 to 4 in which the spot size is less than 10 microns.

6. The method of any one of claims 1 to 5 in which each pulse amplifier comprises dye lasers.

7. The method of claim 2 in which each pulse emerging from the pulse multiplier has about the same duration as the corresponding pulse entering the pulse multiplier.

8. The method of any one of claims 1 to 7 in which the step of generating the principal pulses comprises generating input laser radiation pulses and splitting each input pulse into a pumping pulse and the principal pulse, and wherein, preferably, at least a portion of the amplifiers are pumped with each pumping pulse.

9. The method of claim 8 in which at least a portion of the amplifiers are pumped with the pumping pulse such that there is substantially no pulse-to-pulse variation in the amplification achieved by the amplifiers of the pulse shortening zone.

10. The method of claim 8 in which all of the amplifiers are pumped with the pumping pulse such that there is substantially no pulse-to-pulse variation in the amplification achieved by the amplifiers of the pulse shortening zone.

11. The method of claim 2 comprising the step of pumping the short pulse amplifier with a pumping pulse.

12. The method of any one of claims 1 to 11 in which the duration of each principal pulse is at least 1, and preferably 5, nanosecond and the duration of each corresponding pulse emerging from the last shortener/amplifier stage is less than 100, and, preferably less than 50, 10 or 1 picoseconds.

13. The method of any one claims 1 to 12 in which the duration of each pulse emerging from the last shortener/ amplifier stage is less than about 1/100 of the duration of the corresponding principal pulse.

14. The method of any one of claims 1 to 13 including the step of collimating at least a portion of the pulses to achieve the near Gaussian distribution of the output pulses.

15. The method of any one claims 1 to 14 wherein the step of focusing comprises directing the output pulses through beam delivery means onto the target and focusing imaging signals on the target and collecting signals emanating from the target as a result of the imaging signals into an imaging system, a portion of the path of the signals emanating from the target being collinear with a portion of the path of the output pulses delivered to the target.

16. The method of claim 2 in which the step of multiplying results in the spaced apart pulses being spatially spaced apart from each other.

17. The method of claim 2 or 16 in which the step of amplifying the spaced apart pulses in at least one short pulse amplifier comprises amplifying a portion of the spaced apart pulses more than other spaced apart pulses for producing high power output pulses and low power output pulses, the low power output pulses having less than about 1/100 of the power of the high power output pulses, there being at least two high power output pulses having about the same peak power.

18. The method of any one of claims 1 to 17 in which the step of shortening the duration of each principal pulse comprises focusing each principal pulse into a dye solution at a focus in the dye solution for generating radiation in the dye solution by amplified spontaneous emission, the dye solution absorbing energy from the incoming radiation pulses and the dye solution being contained in a device comprising a front window and a rear window, both windows having an interior surface, the front window transmitting at least a portion of the principal pulses into the dye solution, and wherein both windows are substantially transparent to the generated radiation with the front window reflecting a portion of the incident generated radiation to the focus, and wherein generated radiation passes through the rear window as an outgoing shortened pulse with substantially no reflection of the generated radiation from the rear window to the focus, the focus being at a location between the front and rear windows such that each incoming principle pulse has a single respective outgoing shortened pulse of shorter duration.

19. The method of claim 18 in which the focus is closer to the interior surface of the front window than it is to the interior surface of the rear window, and, preferably, the distance between the focus and the interior surface of the front window is at least 30% of the distance between the two interior surfaces.

20. The method of either claim 18 or 19 wherein the step of focusing the principal pulse comprises moving the optical means for selecting the location of the focus for controlling the duration of the outgoing pulse.

21. The method of claim 2 or 16 in which the step of multiplying each shortened pulse comprises:

(i) directing each shortened pulse into a closed cell comprising a front window and a rear window, both windows having an interior surface and substantially the same index of refraction, the cell containing a medium having an index of refraction substantially equal to the index of refraction of the windows and substantially transparent to the shortened pulse, the cell also containing front and rear opposed reflective means in contact with the medium, the reflective means having a reflectivity of at least about 80% for the incoming shortened pulse, and wherein a portion of the shortened pulse is transmitted through the front window into the cell for reflection back and forth between the front and rear reflective means with a portion of each pulse impinging on the rear reflective means passing through the rear window as one of a series of temporally spaced apart outgoing pulses.

22. The method of claim 21 wherein at least one of the reflective means is curved and including controlling the curvature of the reflective means for causing the outgoing pulses to be spatially spaced apart from each other.

23. The method of either claim 21 or 22 in which the front and rear reflective means comprise the interior surface of the front and rear windows respectively.

24. The method of claim 22 in which the medium is a fluid and the step of controlling the curvature comprises controlling the pressure of the fluid for changing the curvature of at least one of the reflective means for controlling the amount the outgoing pulses are spatially spaced apart from each other.

25. A method for shortening the duration of a lasing radiation pulse comprising the step of focusing an incoming lasing radiation pulse into a dye solution at a focus in the dye solution for generating radiation in the dye solution by amplified spontaneous emission, the dye solution absorbing energy from the incoming pulse, the dye solution being contained in a device comprising a front window and rear window, both windows having an interior surface, the front window transmitting at least a portion of the incoming lasing radiation pulse into the dye solution, wherein both windows are substantially transparent to the generated radiation with the front window reflecting a portion of the incident generated radiation to the focus, and wherein generated radiation passes through the rear window as an outgoing pulse with substantially no reflection of the generated radiation from the rear window to the focus, the focus being at a location between the front and rear windows such that each incoming radiation pulse has a single respective outgoing pulse of shorter duration.

26. The method of claim 25 in which the duration of each outgoing pulse is less than about one half, and preferably 1/10, the duration of its respective incoming pulse.

27. The method of either claim 25 or 26 in which the step of focusing comprises focusing the incoming pulse so that the focus is closer to the interior surface of the front window than it is to the interior surface of the rear window, and preferably the distance between the focus and the interior surface of the front window is at least 30% of the distance between the two interior surfaces.

28. The method of claim 26 wherein the step of focusing comprises moving the optical means for selecting the location of the focus for controlling the duration of the outgoing pulse, and, preferably, amplifying the outgoing pulse.

29. A method for generating a plurality of pulses from a single pulse comprising the steps of:

(a) directing a principal pulse to a pulse multiplier that produces a plurality of temporally and spatially spaced apart pulses for each pulse entering the pulse multiplier; and

(b) amplifying the spaced apart pulses in at least one amplifier for amplifying some of the spaced apart pulses more than other of the spaced apart pulses to produce high power output pulses and low power output pulses, the low power output pulses having substantially less power than the high power output pulses, there being at least two high power output pulses having about the same peak power.

30. The method of claim 29 in which each pulse emerging from the pulse multiplier has about the same duration as the principal pulse entering the pulse multiplier.

31. The method of either claim 29 or 30 including the step of generating an input laser radiation pulse comprising splitting the input pulse into a pumping pulse and the principal pulse and, preferably, pumping the amplifier with at least a portion of the pumping pulse.

32. The method of any one of claim 29 to 31 in which the ratio of the peak power of the high power output pulses to the peak power of the low power output pulses is at least 100:1.

33. A method for generating a plurality of ultra- short laser pulses suitable for focusing on a target to cause a plasma to form in the target, the method comprising the steps of:

(a) generating a principal lasing radiation pulse;

(b) shortening the duration of the principal pulse in a shortening zone by the steps of:

(i) activating a first pulse shortener of a first stage of a series of shortener/amplifier stages, each stage comprising at least one pulse shortener that shortens the duration of the principal pulse and at least one pulse amplifier that amplifies the principal pulse;

(ii) amplifying the shortened pulse emerging from the first pulse shortener in the pulse amplifier of the first stage; and

(iii) directing the lasing radiation pulse emerging from each stage into a pulse shortener of the next successive stage, wherein the pulse emerging from the pulse shortener of each stage is amplified by

the pulse amplifier of that stage before being directed to the next stage;

(c) directing the pulse emerging from the last pulse shortener/amplifier stage to a pulse multiplier that produces a plurality of temporally and spatially spaced apart pulses for each pulse entering the pulse multiplier; and

(d) amplifying the spaced apart pulses in an amplifier zone comprising at least one short pulse amplifier for amplifying some of the spaced apart pulses more than other of the spaced apart pulses for producing high power output pulses and low power output pulses, the low power output pulses having substantially less power than the high power output pulses, there being at least two high power output pulses having about the same peak power.

34. The method of claim 33 in which the principal pulse is shortened by amplified spontaneous emission and the pulse is amplified in the shortening zone with substantially no variation in the amplification from pulse-to-pulse.

35. The method of either claim 33 or 34 in which each pulse emerging from the pulse multiplier has about the same duration as the principal pulse entering the pulse multiplier.

36. The method of any one of claim 33 to 35 in which the step of generating the principal pulse comprises generating an input laser radiation pulse and splitting the input pulse into a pumping pulse and the principal pulse, and preferably in which at least a portion of the amplifiers, including each amplifier of

the amplifier zone, are pumped with the pumping pulse such that there is substantially no pulse-to-pulse variation in the amplification achieved by the amplifiers.

37. The method of any one of claim 33 to 36 in which the ratio of the peak power of the high power output pulses to the peak power of the low power output pulses is at least 100:1.

38. An apparatus for reducing the duration of lasing radiation pulses comprising:

(a) a dye solution capable of absorbing energy from incoming radiation pulses;

(b) means for containing the dye solution comprising a front window and a rear window, both windows having an interior surface, the front window being capable of transmitting at least a portion of the incoming lasing radiation pulses into the dye solution; and

(c) optical means positioned in front of the front window for optically focusing the incoming lasing radiation pulses through the front window into the dye solution at a focus between the windows for generating radiation in the dye solution by amplified spontaneous emission, wherein both windows are substantially transparent to the generated radiation with the front window reflecting a portion of the incident generated radiation to the focus for quenching stimulated emission to prevent lasing, and wherein outgoing generated radiation passes through the rear window as an outgoing pulse with substantially no reflection of the generated radiation from the rear window to the focus, the focus being at a location between the front and rear windows

such that each incoming radiation pulse has a single respective outgoing pulse of shorter duration.

39. The apparatus of claim 38 in which the duration of each outgoing pulse is less than about one half, and, preferably less than 1/10, the duration of its respective incoming pulse.

40. The apparatus of claim 38 in which the focus is closer to the interior surface of the front window than it is to the interior surface of the rear window, and preferably the distance between the focus and the interior surface of the front window is at least 30% of the distance between the two interior surfaces.

41. The apparatus of any one of claims 38 to 40 in which the front and rear windows are planar.

42. The apparatus of any of claims 38 to 41 in which the front window transmits at least 90% of the incoming radiation pulses into the dye solution.

43. The apparatus of any one of claims 38 to 42 in which the rear window reflects less than about 10% of the generated radiation impinging upon.

44. The apparatus of any one of claims 38 to 43 including means for moving the optical means for selecting the location of the focus for controlling the duration of the outgoing radiation pulse.

45. An apparatus for converting an incoming lasing radiation pulse into a plurality of temporally and spatially spaced apart outgoing pulses comprising:

(a) a closed cell comprising a front window and a rear window, both windows having an interior surface and substantially the same index of refraction;

(b) a medium in the cell having an index of refraction substantially equal to the index of refraction of the windows and substantially transparent to the incoming lasing radiation pulse;

(c) front and rear opposed reflective means in the interior of the cell in contact with the medium, the reflective means having a reflectivity of at least about 80% for the incoming lasing radiation pulse;

wherein a portion of the incoming lasing radiation pulse is transmitted through the front window into the cell for reflection back and forth between the front and rear reflective means with a portion of the pulse impinging on the rear reflective means passing through the rear window as one of a series of temporally spaced apart outgoing lasing radiation pulses.

46. The apparatus of claim 45 in which the front and rear reflective means comprise the interior surface of the front and rear windows, respectively.

47. The apparatus of claim 45 in which the windows are spaced apart from each other by a distance of from about 1 to about 100 mm, and preferably from about 5 to about 20 mm.

48. The apparatus of claim 45 in which the interior surface of both windows has a reflectivity of at least about 85% for the incoming lasing radiation pulse.

49. The apparatus of any one of claims 45 to 48 including means for amplifying the outgoing lasing radiation pulses.

50. The apparatus of claim 49 in which the outgoing lasing radiation pulses are amplified by the amplifying means so that at least five pulses have about the same peak power.

51. The apparatus of any one of claims 45 to 50 in which each outgoing pulse has about the same duration as the duration of each incoming pulse.

52. The apparatus of any one of claims 45 to 51 in which the outgoing pulses when focused are spatially spaced apart from each other by at least one micron, and preferably 10 microns.

53. Apparatus for forming a plasma in a target with ultrashort pulses comprising:

(a) means for generating a plurality of principal lasing radiation pulses;

(b) means for shortening the duration of each principal pulse to form a corresponding shortened output pulse, the shortening means comprising a series of shortener/amplifier stages, each stage comprising at least one pulse shortener that shortens the duration of each principal pulse by amplified spontaneous emission with substantially no lasing and at least one pulse

amplifier that amplifies each principal pulse with substantially no pulse-to-pulse variations in the amplification from pulse- to-pulse, the stages being arranged for directing lasing radiation pulses emerging from each stage into a pulse shortener of the next successive stage, wherein the pulse emerging from the pulse shortener of each stage is amplified by the pulse amplifier of that stage with substantially no pulse-to-pulse variations in the amplification from pulse-to-pulse before being directed to the next stage; and

(c) focusing means for focusing the output pulses into a sufficiently small spot size in the target to achieve an irradiance of at least 10^{13} watts/cm^2 in the target for forming a plasma in the target irrespective of whether the target is absorbing or non-absorbing for the output pulses.

54. The apparatus of claim 53 in which the spot size is less than 10 microns.

55. The apparatus of either claim 53 or 54 in which each pulse amplifier comprises a dye laser.

56. The apparatus of any one of claims 53 to 55 in which the means for generating the principal pulse comprises laser means for generating an input laser radiation pulse and means for splitting the input pulse into a pumping pulse and the principal pulse, and preferably including means for directing at least a portion of the pumping pulse to at least a portion of the amplifiers for pumping the amplifiers.

57. The apparatus of any one of claims 53 to 56 in which the duration of each pulse emerging from the last shortener/amplifier stage is less than about 1/100 of the duration of the corresponding principal pulse.

58. The apparatus of any one of claims 53 to 57 including means for collimating lasing radiation pulses to achieve a near Gaussian distribution of the pulses incident on the optical means.

59. The apparatus of any one of claims 53 to 58 wherein the focusing means comprises (i) means for directing the output pulses to the target, (ii) means for directing imaging signals to the target, and (iii) collection means for collecting signals emanating from the target as a result of the imaging signals, a portion of the path of the signals emanating from the target being collinear with a portion of the path of the output pulses directed to the target.

60. Apparatus for forming a plasma in a target comprising:

(a) means for generating a principal lasing radiation pulse;

(b) means for shortening the duration of the principal pulse comprising a series of shortener/amplifier stages, each stage comprising at least one pulse shortener that shortens the duration of the principal pulse and at least one pulse amplifier that amplifies the principal pulse, the stages being arranged for directing lasing radiation pulses emerging from each stage into a pulse shortener of the next successive stage, wherein the pulse emerging from the pulse shortener of each stage is amplified by the pulse

amplifier of that stage before being directed to the next stage;

(c) a pulse multiplier for multiplying the pulse emerging from the last pulse shortener/amplifier stage for producing a plurality of temporally spaced apart pulses for each pulse entering the pulse multiplier;

(d) at least one short pulse amplifier for amplifying the spaced apart pulses to produce output pulses, the output pulses having a duration of less than 100 picoseconds and having a near Gaussian distribution; and

(e) optical means for focusing the output pulses into a sufficiently small spot size in the target to achieve an irradiance of at least 10^{13} watts/cm^2 in the target for forming a plasma in the target irrespective of whether the target is absorbing or non-absorbing for the output pulses.

61. The apparatus of claim 60 wherein the pulse shorteners operate by amplified spontaneous emission without lasing.

62. The apparatus of either claim 60 or 61 wherein there is substantially no pulse-to-pulse variation in the power of the pulses from the shortener/amplifier stage.

63. The apparatus of any one of claims 60 to 62 in which the spot size is less than 10 microns.

64. The apparatus of any one of claims 60 to 63 in which each pulse emerging from the pulse

multiplier has about the same duration as the pulse entering the pulse multiplier.

65. The apparatus of any one of claims 60 to 64 in which the means for generating the principal pulse comprises a laser for generating an input laser radiation pulse and means for splitting the input pulse into a pumping pulse and the principal pulse and, preferably, including means for directing at least a portion of the pumping pulse to at least a portion of the amplifiers, including the short pulse amplifier, for pumping the amplifiers.

66. The apparatus of any one of claims 60 to 65 in which the duration of the pulse emerging from the last shortener/ amplifier stage is less than about 1/100 of the duration of the principal pulse.

67. The apparatus of any one of claims 60 to 66 wherein the spaced apart pulses are spatially spaced apart from each other.

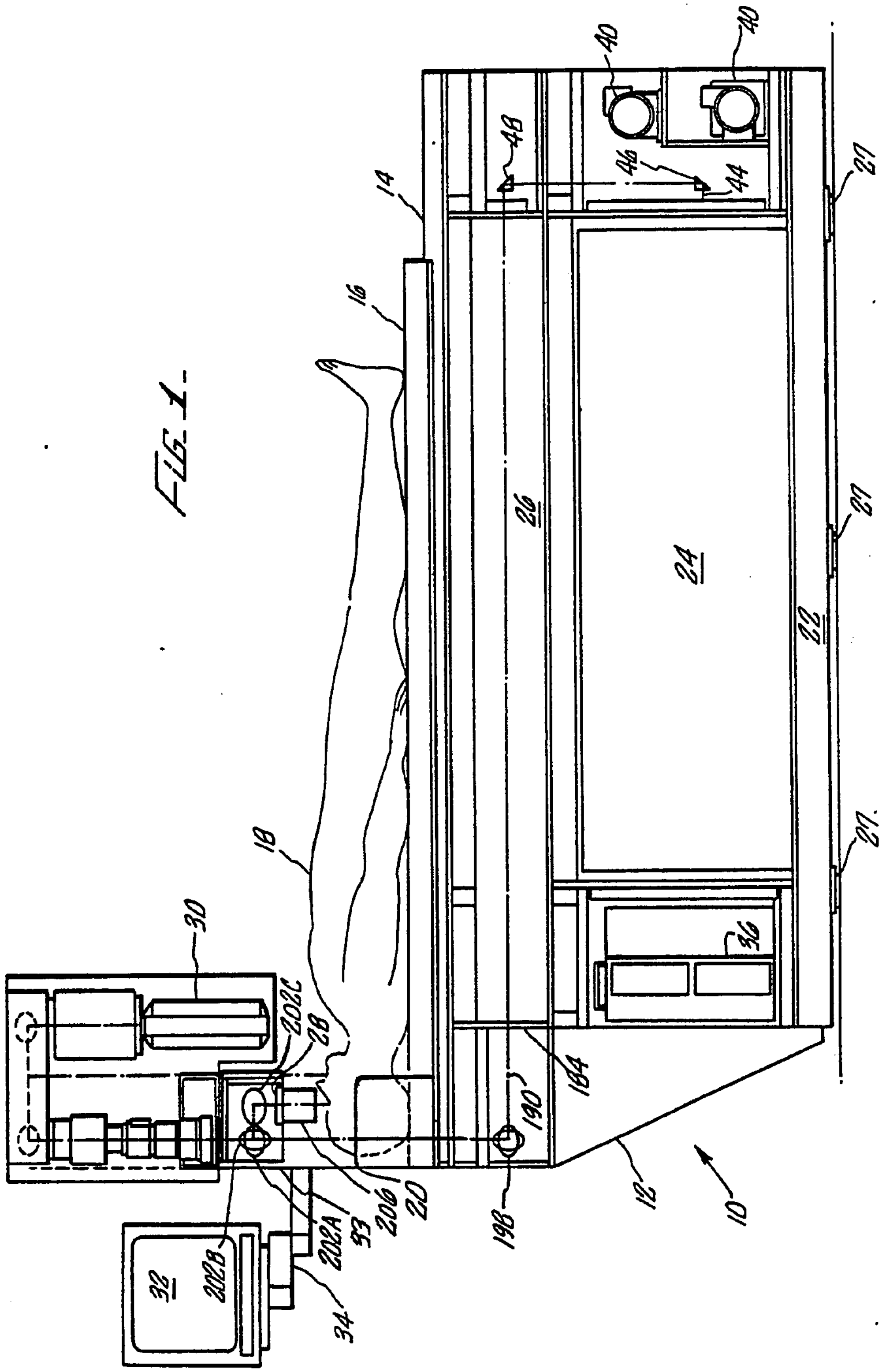

FIG. 1

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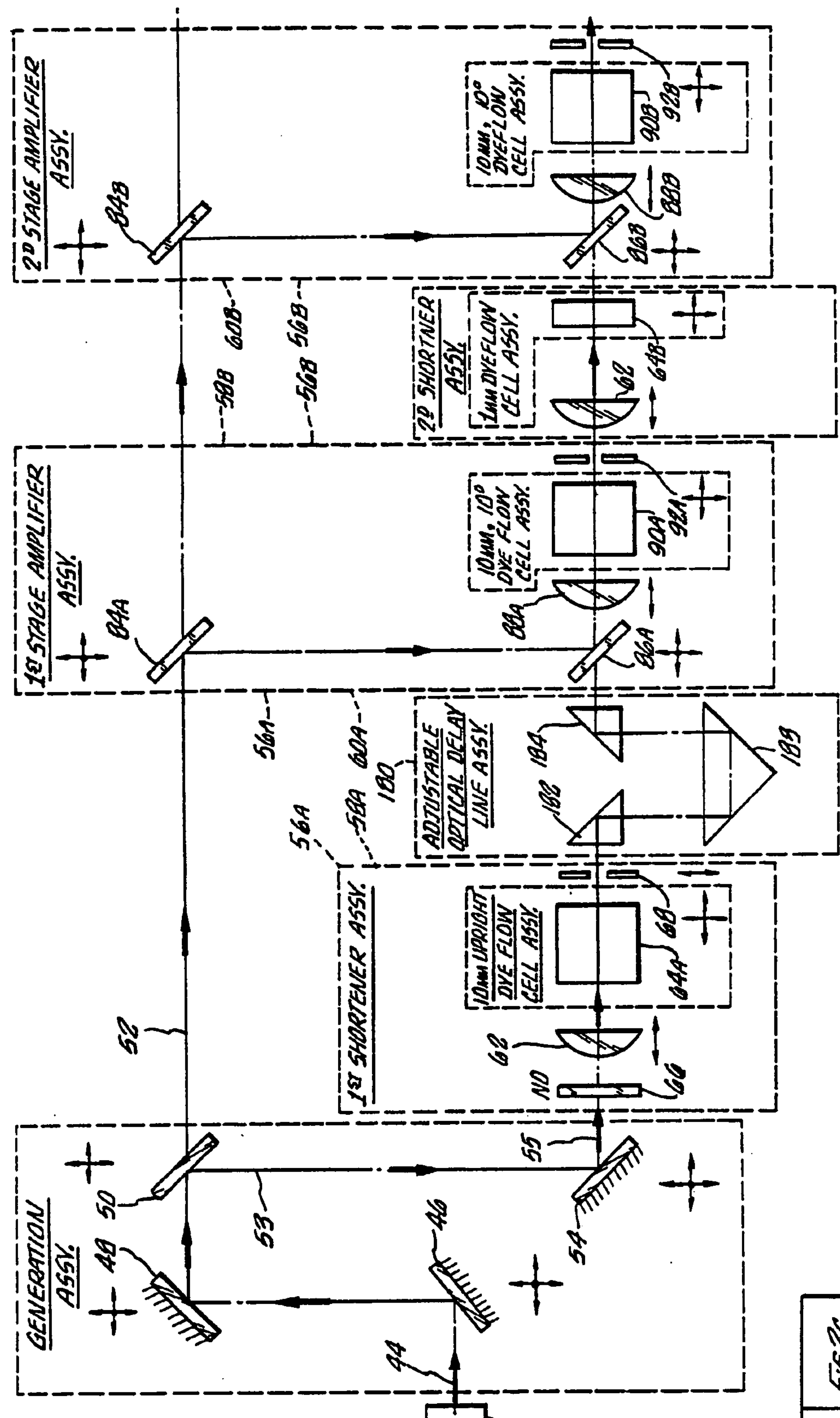

FIG. 2B.

FIG.2B. FIG.2C.

FIG.2A.

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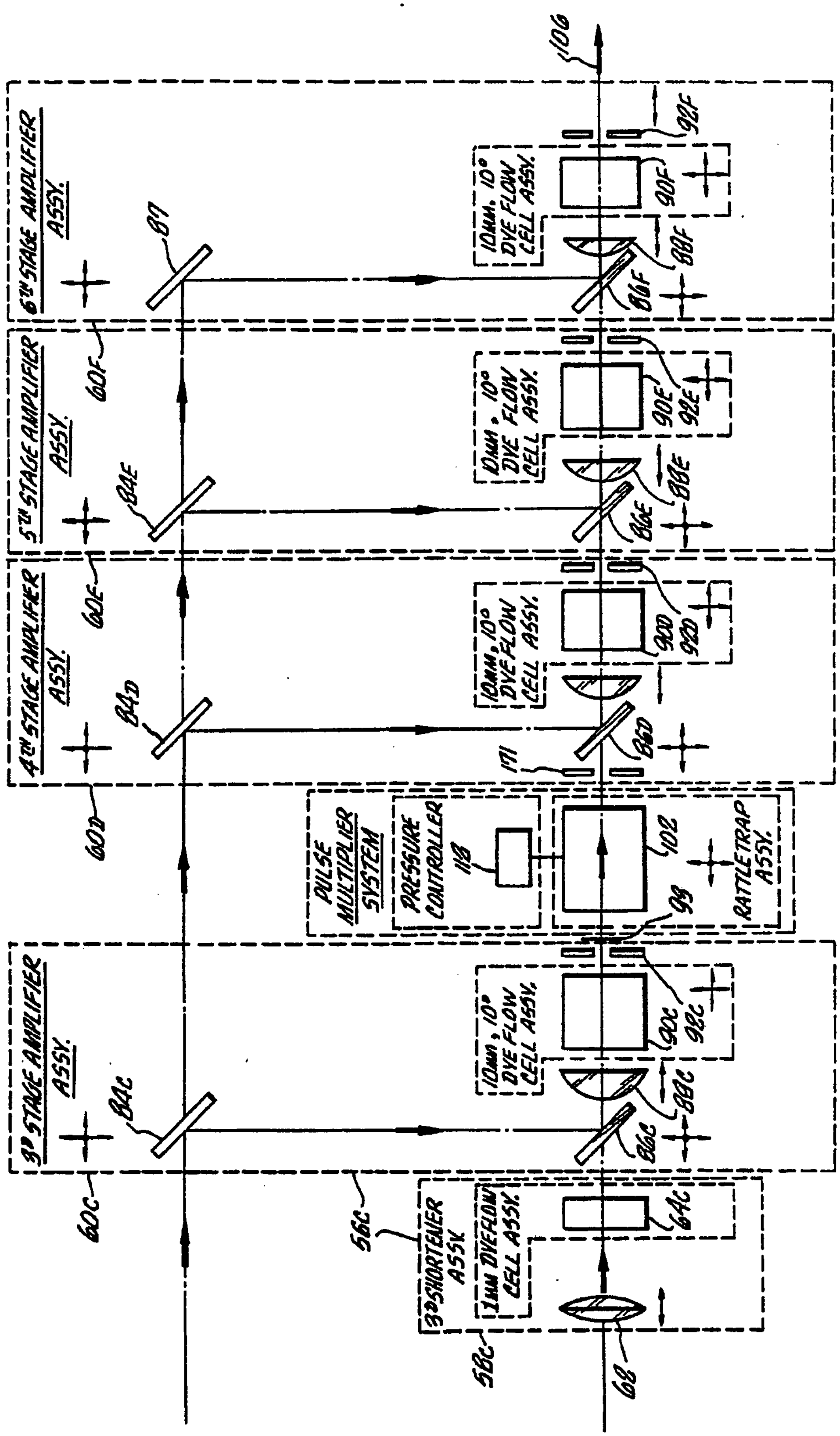

FIG. 8C.

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FIG. 3

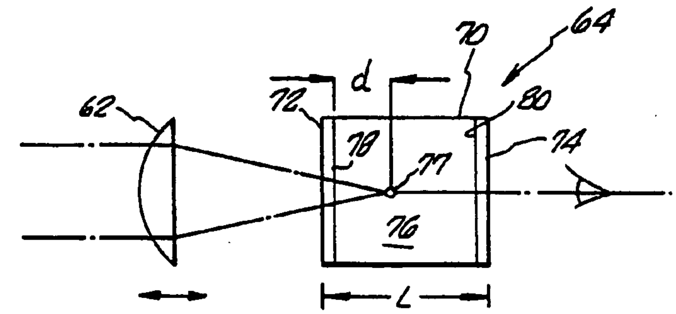


FIG. 4

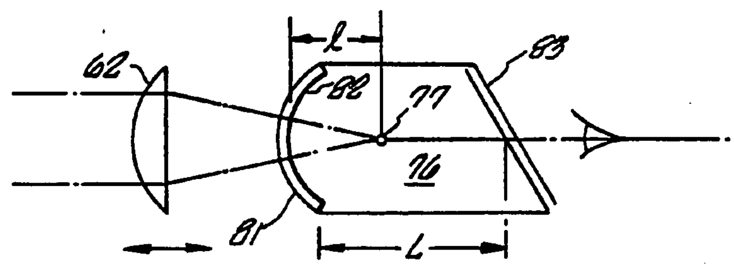
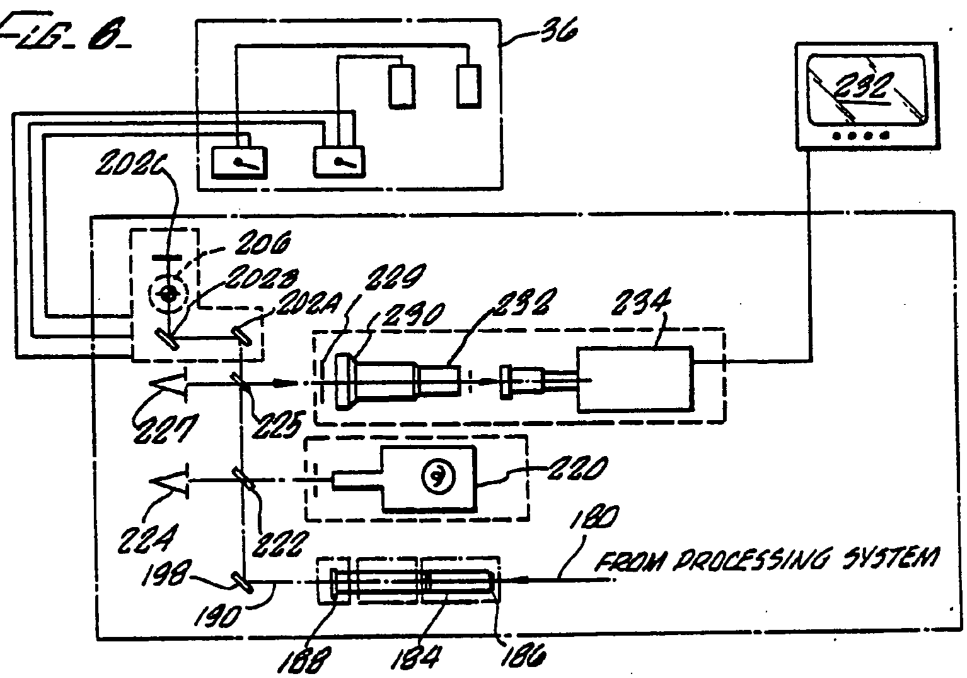


FIG. 6



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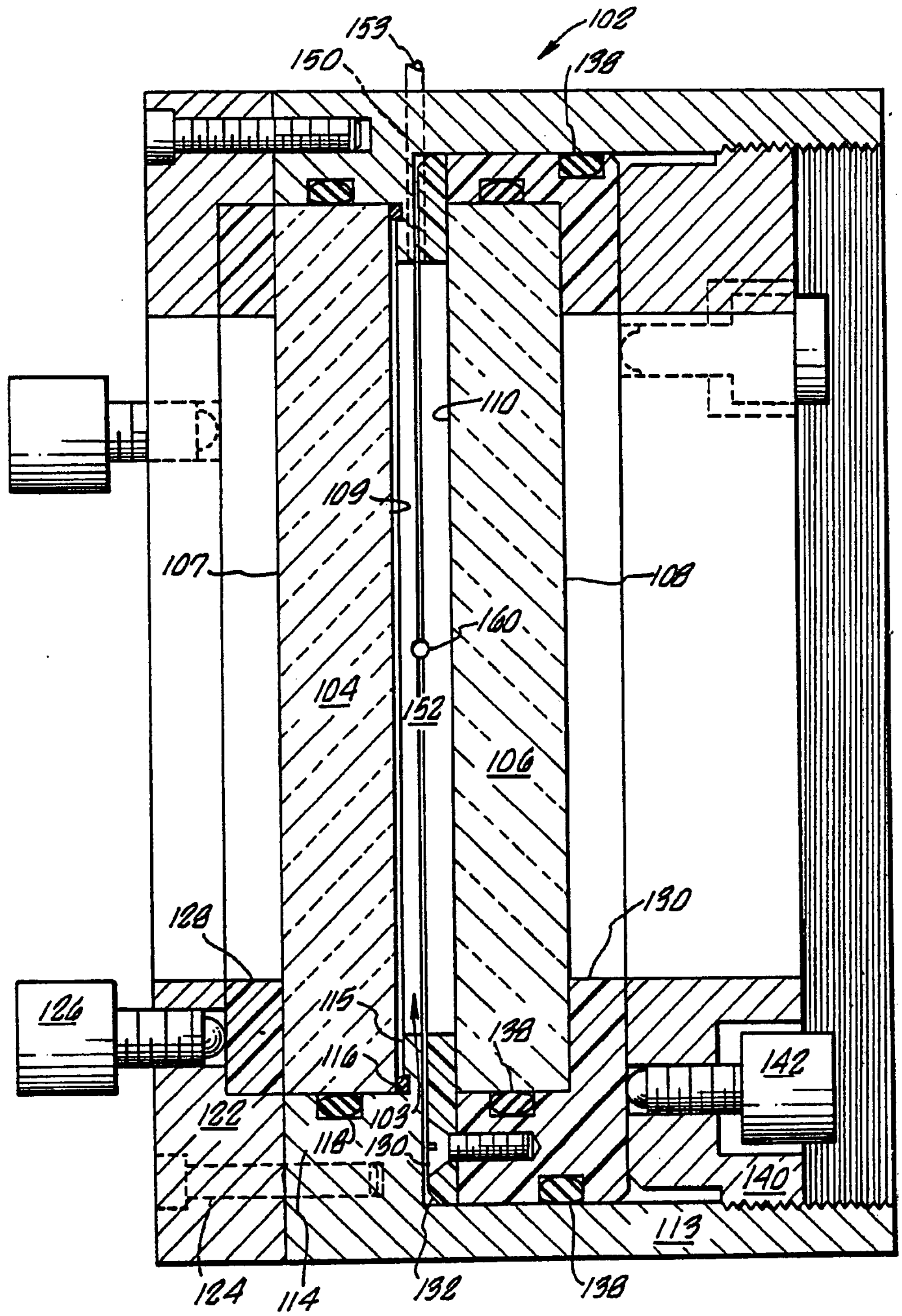

FIG. 5.

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INTERNATIONAL SEARCH REPORT

International Application No PCT/US87/00966

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC (4): A61N 5/06
U.S. Cl. 128/303.1

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
U.S.	128/303.1, 362, 395 356/171, 312 372/1, 5, 25, 29, 30, 31

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
X Y	Optics Communications, Volume 29, No. 1, April 1979, Y. Taira et al, "High Power Subpicosecond Pulse Generation from a Synchronously Pumped Dye Laser Combined with an External Compressor," see pages 115-118.	25-28, 38-40 43/38-40, 44/38-40 1-24, 29-37, 41-67
Y	US, A, 3,657,554 (LUMPKIN ET AL) 18 April 1972, see Figure 1, column 3, lines 11-37.	41, 42, 43/41, 42
Y, P	US, A, 4,630,274 (SCHAFER) 16 December 1986, see column 1, lines 9-37, column 5, line 58-column 6, line 2.	1-24, 53-58
Y	US, A, 3,889,208 (ITZKAN) 10 June 1975 See column 2, lines 24-27.	5, 6/5, 54, 56/54, 57/54, 58/54
X Y	US, A, 4,200,846 (STARK, JR. ET AL.) 29 April 1980, see Figure 3, column 2, line 47-column 3, line 11.	29-31 2-24, 32-37, 45-52, 60-67

* Special categories of cited documents: [15]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [3]
21 August 1987	11 SEP 1987
International Searching Authority [1]	**Signature of Authorized Officer** [20]
ISA/US	David Shay

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International Application No. PCT/US87/00966

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No [18]
Y, P	US, A, 4,643,186 (ROSEN ET AL.) 17 February 1987, see Figures 7a, 7b and 8, see also abstract and column 6, lines 38-68.	22, 24
Y	Applied Physics, Vol. 15, No. 3, issued March 1978, H.P. Grieneisen et al., "Coherence and Beam Geometry of a Superradiant Dye Laser," see Figure 1, see pages 281-282.	19, 20, 27, 28
Y	S. Trokel, "YAG Laser Ophthalmic Microsurgery", published by Appleton-Century-Crofts (Norwalk, CT, USA), 1983, see pages 14 and 71-77.	1-24, 53-67
Y	US, A, 3,783,874 (KOESTER ET AL.) 08 January 1974, see Figures 2-4 and column 6, line 50-column 8, line 39.	15, 59
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FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

Y	US, A, 4,059,759 (HARNEY ET AL.) 22 November 1977, see the entire document.	2-24, 29-37, 45-52, 60-67
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Y	JA, A, 0,068,995 (URISU) 25 April 1983 See the entire document.	45-52
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V. ☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE [10]

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1. ☐ Claim numbers , because they relate to subject matter [12] not required to be searched by this Authority, namely:

2. ☐ Claim numbers ..... , because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out [13], specifically:

VI. ☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING [11]

This International Searching Authority found multiple inventions in this international application as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.
2. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:
3. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:
4. ☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

☐ The additional search fees were accompanied by applicant's protest.

☐ No protest accompanied the payment of additional search fees.